ADA

FEASIBILITY OF USING FULL SYNTHETIC LOW VISCOSITY ENGINE OIL AT HIGH AMBIENT TEMPERATURES IN U.S. ARMY ENGINES

INTERIM REPORT
TFLRF No. 413

by
Edwin A. Frame
Adam C. Brandt
Ruben A. Alvarez, Sr.

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Allen S. Comfort
Luis A. Villahermosa

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. DAAE-07-99-C-L053 (WD42)

June 2011

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14. ABSTRACT Advancements in lubricant technology over the last two decades, in particular, the availability of high quality synthetic base oils, has set the stage for the development of a new fuel efficient, multifunctional powertrain lubricant with extended drain capabilities. Given its large fleet size, diversity of equipment, and range of environments in which it must operate, the U.S. Army is perhaps uniquely positioned to benefit from these advancements. This report summarizes the initial work that the U.S. Army's Fuel and Lubricants Technology Team has been doing to establish the technical feasibility of developing a new multifunctional, fuel efficient powertrain lubricant for the Army's fleet of combat and tactical vehicles and equipment – referred to as the Single Common Powertrain Lubricant (SCPL) project. The feasibility of using a low viscosity diesel engine oil in Army engines was determined. At desert like operating conditions, a prototype SCPL provided similar overall performance as an SAE15W.40 oil in 3 Army engines.

15. SUBJECT TERMS

Arctic engine oil, 6.5L engine, CAT C-7, DDC Series 60, NATO 400 hour test, 210 h wheeled vehicle test cycle, synthetic engine oil

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EXECUTIVE SUMMARY

The U.S. Army investigated the technical feasibility of a Single Common Powertrain Lubricant (SCPL). This new lubricant would consist of an all-season (arctic to desert), fuel efficient, multifunctional powertrain fluid with extended drain capabilities. As a developmental starting point, the effect of operating U.S. Army diesel engines using low viscosity engine oil at increased oil temperature was examined. Engine testing has been conducted using MIL-PRF-46167D arctic engine oil at high temperature conditions representative of desert operation. Testing has been completed using three high density military engines: the General Engine Products 6.5L(T) engine, the Caterpillar C7, and the Detroit Diesel Series 60. Tests were conducted following two standard military testing cycles; the 210 h Tactical Wheeled Vehicle Cycle, and the 400 h NATO Hardware Endurance Cycle. Modifications were made to both testing procedures to more closely replicate the operation of the engine in desert like conditions. These modifications included operation at elevated oil sump (nominally 260 °F) and water jacket (nominally 205 °F) temperatures. Test engines completed an initial tear down, inspection, and metrology process prior to being built to manufacturer supplied specifications for testing. After completion of testing all engines were again disassembled and underwent a complete metrology and component rating process to determine overall engine wear and deposits. Results have shown promising data for use of low viscosity crankcase lubricants operated at high temperatures in U.S. Army diesel engines.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period of August 2006 through June 2011 under Contract No. DAAE-07-99-C-L053. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSRD-TAR-D/MS110) served as the TARDEC contracting officer's technical representative. Mr. Allen S. Comfort of TARDEC served as project technical monitor.

The author would also like to recognize the contribution of Dianna Barrera for her administrative and report-processing support, and the TFLRF engine laboratory technical staff.

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ACRONYMS AND ABBREVIATIONS

ABS/cm	Absorbance / centimeter
API	American Petroleum Institute
CAT	Caterpillar
cSt	Centistokes
DDC	Detroit Diesel Corporation
FMTV	Family of Medium Tactical Vehicles
GEP	General Engine Products
HDO	Heavy Duty Oil
HMMWV	High Mobility Multipurpose Wheeled Vehicle
Hp	Horsepower
H	Hours
HTV	Heavy Tactical Vehicle
ICP	Inductively Coupled Plasma
KOH/g	Potassium Hydroxide / gram
MATV	MRAP All Terrain Vehicle
MRAP	Mine Resistant Ambush Protected
NATO	North Atlantic Treaty Organization
OE	Oil Engine
OEA	Oil Engine Arctic
PPM	Parts Per Million
Psi	pounds per square inch
RPM	Revolutions Per Minutes
SAE	Society of Automotive Engineers
SCPL	Single Common Powertrain Lubricant
SwRI®	Southwest Research Institute®
TACOM	Tank and Automotive Command
TAN	Total Acid Number
TARDEC	Tank-Automotive RD&E Center
TBN	Total Base Number
TFLRF	TARDEC Fuel and Lubricants Research Facility
TGA	Thermo Gravimetric Analysis
TWV	Tactical Wheeled Vehicle
TWVC	Tactical Wheeled Vehicle Cycle
VIS	Viscosity
WD	Work Directive
wt%	Weight Percent

1.0 INTRODUCTION

The U.S. Army has a desire to consolidate multiple lubricant specifications into a single specification, or Single Common Powertrain Lubricant (SCPL). The application of this fluid would range from engine lubrication to power shift transmission operation, and must be designed to operate in ambient conditions ranging from low temperature arctic to high temperature desert type conditions. By achieving these goals, multiple specifications could be reduced into a single specification and lubricant that could be used in all tactical or combat vehicles, despite the seasonal or geographical location. The development of this fluid would reduce the logistical burden on the military's supply chain by only requiring one lubricant to be procured and distributed throughout its worldwide operations. Due to the extreme operational requirements, it is likely that this SCPL will be formulated from higher cost synthetic base stocks as compared to traditional petroleum derived lubricants. To offset the increased cost of using synthetic lubricants, several performance goals must be met such as increased fuel efficiency and extended drain intervals. Current research has shown the potential reduction in fuel consumption with the use of low viscosity lubricating fluids. This reduction in fuel consumption is attributed to the reduction in mechanical losses within the system including frictional, pumping, and churning losses. Although these reductions in fuel consumption are expected to be relatively small, when multiplied over a large fleet such as the military's combat and tactical fleet, the cost savings can be substantial. In addition, the use of synthetic base stocks will provide increased resistance to oil degradation allowing the extension of time between required oil drain, also increasing the cost effectiveness of the SCPL.

2.0 TECHNICAL FEASIBILITY

2.1 Low Viscosity Engine Oil Durability

Although fuel efficiency has been a critical design goal for passenger cars for well over a decade, the heavy-duty vehicle segment has traditionally focused on durability, with much less regard to fuel efficiency. This is a natural consequence of the demands of customers who are mainly large fleet operators looking to maximize the time between engine overhauls. Expectations for modern

engines are well over 15,000 hours or 500,000 miles between overhauls. In contrast, the U.S. Army's fleet of tactical and combat vehicles will, on average, accumulate much less than 100,000 miles over a lifetime. This difference in operation potentially allows for some flexibility in lubricant selection and formulation that otherwise would not be permissible. For example, the approach of utilizing low viscosity engine oils to improve fuel economy has been well documented in the literature (Taylor and Coy, 1999; Taylor, 2000; Lechner et al., 2002; Adamski et al., 2008). Even so, this approach has been largely ignored by heavy-duty engine manufacturers because of concerns that this would increase wear rates and reduce time between overhauls (Rosenbaum, 2010; Fox, 2005). Such a concern is clearly reduced for vehicles that average less than 100,000 miles over a lifetime. Despite reduced lifetime miles, military vehicles must be dependable and a premium is put on readiness.

To establish that low viscosity heavy duty engine oil will have the required durability, a qualified MIL-PRF-46167 OEA-30 oil (Ref. 1) was chosen as a starting point and tested in a variety of military engines representing the light, medium, and heavy tactical fleet. OEA-30 is a full synthetic, arctic engine oil used in military combat and tactical equipment at ambient temperatures ranging from -50 °F to 90 °F. The OEA-30 was chosen as a prototype SCPL because it is a low viscosity lubricant with a long history of successful use in military applications. Tests were conducted following two standard military testing cycles; the 210 hour Tactical Wheeled Vehicle Cycle, and the 400 hour NATO Hardware Endurance Cycle. However, modifications were made to both testing procedures to more closely replicate the operation of the engine in desert-like conditions. These modifications included operation at elevated oil sump (nominally 260 °F) and water jacket (nominally 205 °F) temperatures. Test engines completed an initial tear down, inspection, and metrology process prior to being built to manufacturer supplied specifications for testing. After completion of testing all engines were again disassembled and underwent a complete metrology and component rating process to determine overall engine wear and deposits. A test report for each engine test that evaluated low viscosity Arctic engine oil is included in the Appendices. The baseline engine test reports are available in references 4-6.

3.0 TEST ENGINES

Three high density military engines were selected for initial testing as a way to determine SCPL impact on a large portion of the current military fleet. The test engines were selected to be representative of light, medium, and heavy-duty military vehicles, and consisted of the: General Engine Products 6.5L(T), Caterpillar C7, and Detroit Diesel Series 60 engine.

3.1 General Engine Products 6.5L(T)

The General Engine Products (GEP) 6.5L(T) is a 6.5 L V8 non-intercooled turbocharged diesel engine. Its valvetrain consists of a cam in block arrangement with roller followers, pushrods, and overhead rockers actuating 2-valves per cylinder. The indirect (pre-chamber) fuel injection system utilizes a fuel lubricated rotary style injection pump in a pump line nozzle configuration. It is rated at 190 hp @ 3400 rpm, and 380 lb*ft of torque @ 1800 rpm using diesel fuel. The GEP 6.5L(T) and its 6.5 L and 6.2 L naturally aspirated counter parts are commonly used in all variants of the High Mobility Multipurpose Wheeled Vehicle (HMMWV). Figure 1 below shows the GEP 6.5L(T) test stand installation.

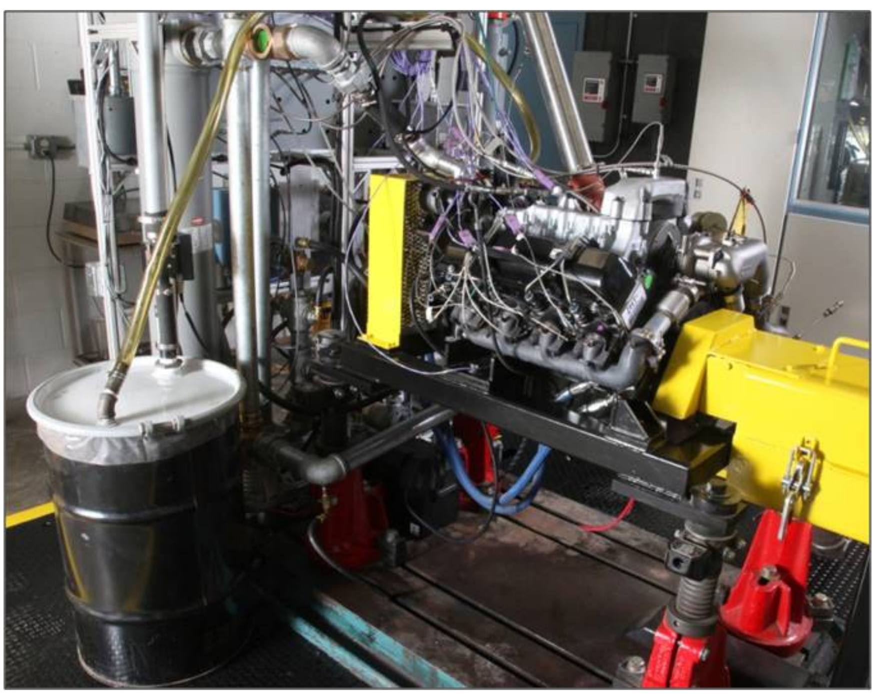

Figure 1. GEP 6.5L(T) Test Cell Installation

3.2 Caterpillar C7

The Caterpillar (CAT) C7 ACERT engine is a 7.2 L direct injected turbocharged intercooled diesel engine. Its valvetrain consists of a cam in block arrangement with roller followers, pushrods, and overhead rockers with valve bridges to actuate the 3-valves per cylinder. It uses a hydraulically actuated electronically controlled unit injection (HEUI) fuel system that consists of an oil lubricated high pressure oil pump for hydraulic power. The engine is rated at 330 hp @ 2400 rpm, and 860 lb*ft of torque @ 1440 rpm using diesel fuel. The CAT C7 engine is commonly used in the Family of Medium Tactical Vehicles (FMTV), the IAV Stryker, some Mine Resistant Ambush Protected (MRAP) variants, and the MRAP All Terrain Vehicle (M-ATV). Figure 2 below shows the CAT C7 test cell installation.

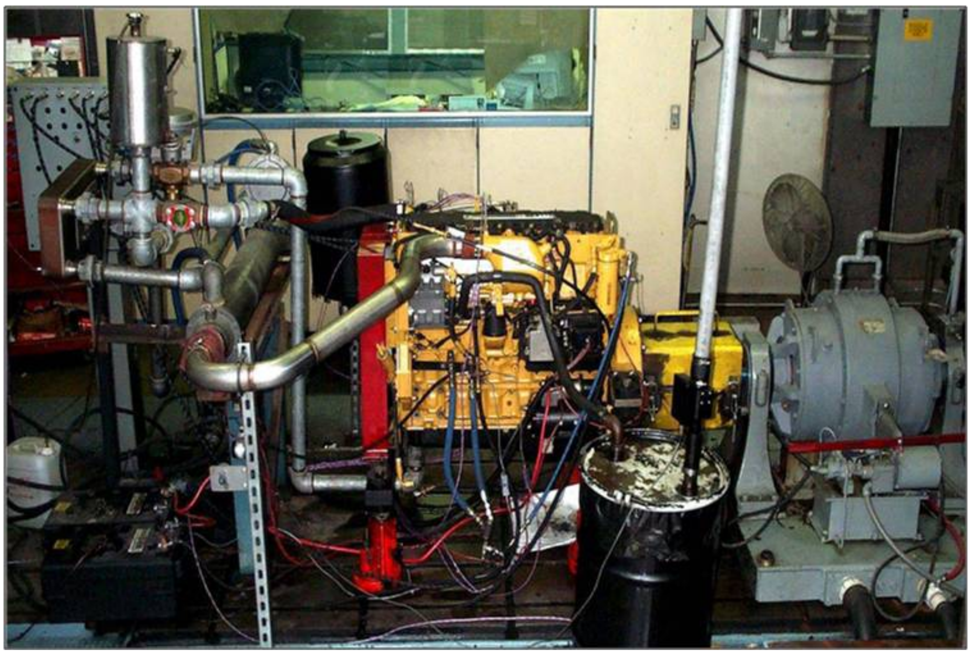

Figure 2. Caterpillar C7 Test Cell Installation

3.3 Detroit Diesel Series 60

The Detroit Diesel Corporation (DDC) Series 60 DDEC III engine is a 12.7 L direct injected turbocharged intercooled diesel engine. Its valve train consists of an overhead camshaft actuating roller rocker arms that actuate 4-valves per cylinder. It uses electronically controlled unit

injectors that are actuated from the overhead camshaft by roller rocker arms. The engine is rated at 375 hp @ 2100 rpm, and 1350 lb*ft of torque @ 1200 rpm using diesel fuel. The engine was from the family of Heavy Tactical Vehicles (HTV), including the Army M915, M916, and M917 trucks, and equipped with an air compressor and Jake Brake assembly. The Jake Brake assembly was physically installed but was electrically deactivated for this testing. Figure 3 below shows the DDC Series 60 test stand installation.

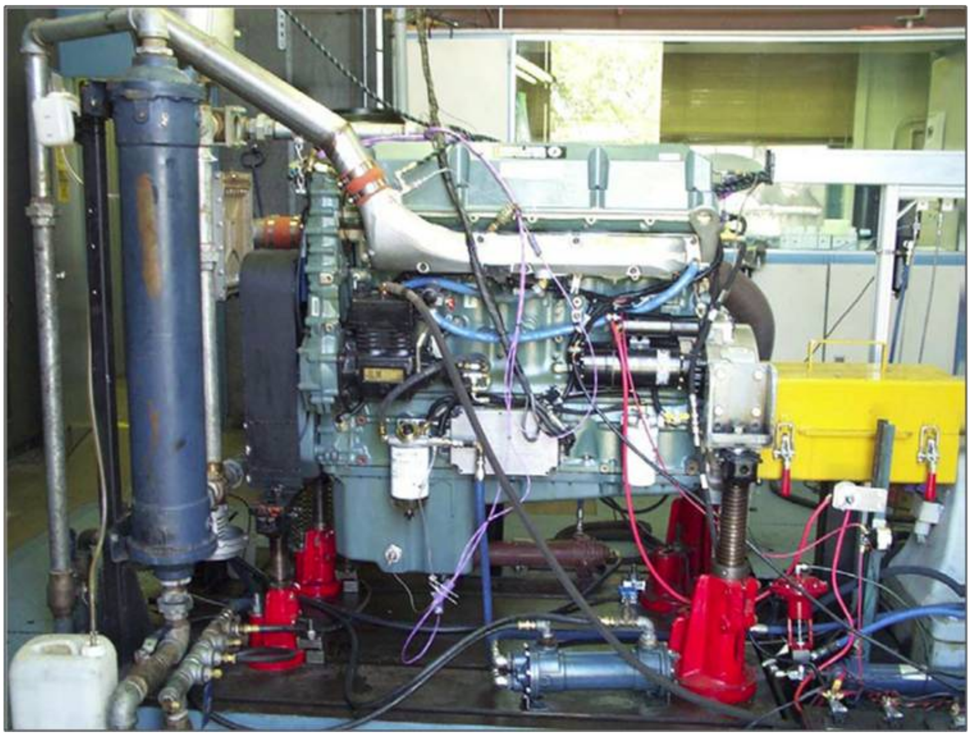

Figure 3. Detroit Diesel Corporation Series 60 Test Cell Installation

4.0 TEST CYCLES

All testing was completed using the flowing standard military test cycles, operating on JP-8 fuel. Modifications to each cycle were made to replicate conditions similar to those found during desert type operation. These changes included operation at elevated oil sump (nominally 260 °F) and water jacket (nominally 205 °F) temperatures. Brief descriptions of each cycle are shown below.

4.1 Tactical Wheeled Vehicle Engine Cycle

The Tactical Wheeled Vehicle cycle is a 210 h procedure initially designed to qualify fuels and lubricants for military usage, and has been shown to be equivalent to approximately 20 20,000 miles of proving ground operation in military equipment (Ref. 2). It consists of alternating engine operation of 2 h at full load rated conditions, and 1hr at idle conditions, for a total of 14 h of testing and 10 h of soaking daily. Pre and post test power curve checks are completed before and after testing to determine changes in engine performance. No oil changes are made to the engines during testing. Oil condition is monitored daily, and testing is ended upon 210 h of test time, or major oil degradation, whichever occurs first.

4.2 NATO Standard Engine laboratory Test

The NATO test cycle (Ref. 3) is a 400 h procedure designed to test hardware endurance for use in military equipment. It consists of 400 h of engine operation at multiple points over the engine map. The cycle is operated for 20 h per day followed by a 4 h soak. The test cycle operating conditions can be condensed down to repeating cycle for every 10 h of operation. Each 10 h segment of testing subjects the engine to the following conditions (Table 1):

Table 1. 400 h NATO Cycle Test Conditions

Duration (h)	% Rated Speed	% Load
0.5	Idle	0
2	100	100
0.5	Governed Speed	0
1	75	100
2	Idle - 100	0 - 100
0.5	60	100
0.5	Idle	0
0.5	Governed Speed	70
2	Max Torque	100
0.5	60	50

Engine oil changes are allowed at every 100 h interval, and powercurve checks are completed at the start, end, and every 100 h of test time to determine changes in engine performance.

4.3 Tactical Wheeled Vehicle Engine Cycle Results

Results of the Tactical Wheeled Vehicle Cycle are presented below. End of testing used oil analyses for both baseline and candidate fluids in each respective engine are presented in Table 2. The OEA-30 had equivalent or better overall performance compared to the baseline oil, MIL-PRF-2104G (Ref. 7) in all three tested engines.

Table 2. EOT Oil Analysis Results

	Engine	GEP 6.5L(T)		CAT C7		DDC Series 60	
Properties	Units	Baseline	OEA-30	Baseline	OEA-30	Baseline	OEA-30
Total Test Time on Oil	Hrs	196	210	420	630	210	210
Viscosity @ 100°C	cSt	31.4	14.83	13.3	9.52	12.8	9.52
TAN	KOH/g	11.3	9.8	3.4	3.4	2.3	2.5
TBN	KOH/g	0.1	2.2	3.5	5.0	4.5	2.3
Oxidation	Abs/cm	149	141.7	13.4	11.28	4.04	11.28
Nitration	Abs/cm	5.44	31.52	0.28	0.28	N/A	N/A
Soot	Wt%	3.2	3.3	1.0	1.0	0.4	0.5
Wear Metals	ppm						
Fe		555	986	93	71	20	35
Cu		170	475	83	12	15	7
Pb		1424	1679	2	7	5	6

Severe oil degradation was observed with the GEP 6.5L(T) engine when operated at 260 °F oil sump temperature. The baseline test was terminated at 196 hours due to major oil degradation, while the OEA-30 was able to finish the 210 hour test cycle. In both cases the oil was pushed past the point at which used oil analysis conditions indicated that an oil change was needed to determine maximum possible oil life. When comparing the used oil analysis for both tests, the oil condition indicated that an oil change was needed for the baseline test at approximately 112 hours based on a criterion of a minimum TBN of 2. By 140 hours all TBN was depleted, while the OEA-30 TBN remained above 2 until around 180 hours. Both oils experienced large increases in Total Acid Number (TAN) and depletion of the Total Base Number (TBN) throughout testing, as well as substantial accumulations of wear metals attributed to main and connecting rod bearing wear. Despite both oil's extreme degradation, the OEA-30 oil did appear to perform better overall, as evidenced by TAN/TBN crossover later in the test. Figures 4 and 5, respectively, show the TAN/TBN and viscosity response of the baseline and OEA-30 oil for the GEP 6.5L(T) engine.

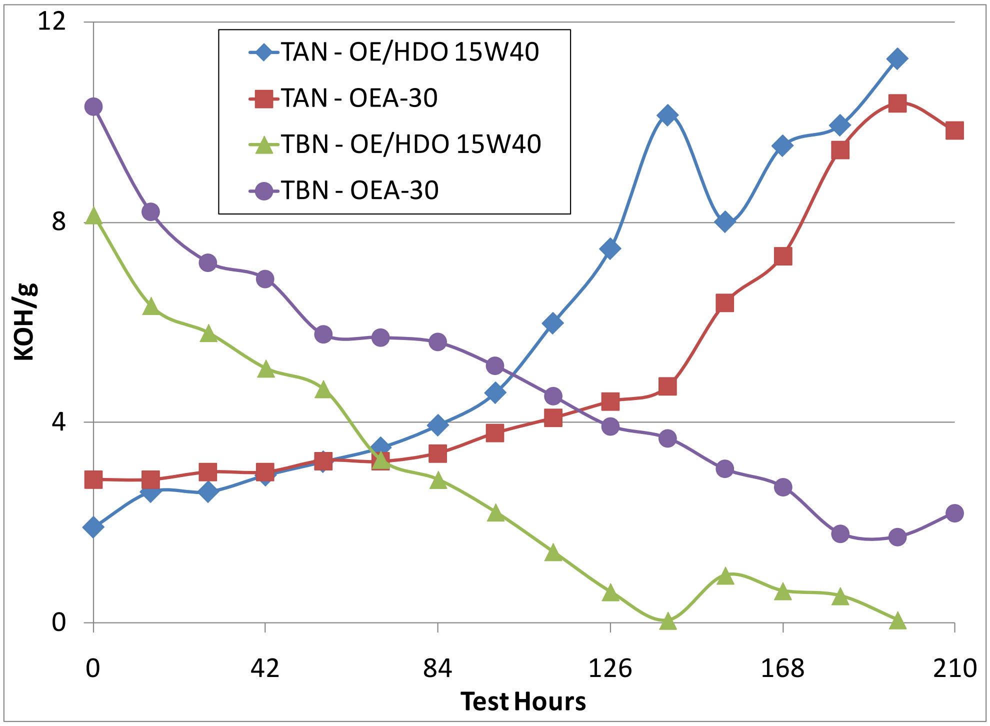

Figure 4. GEP 6.5L(T) TAN/TBN Response

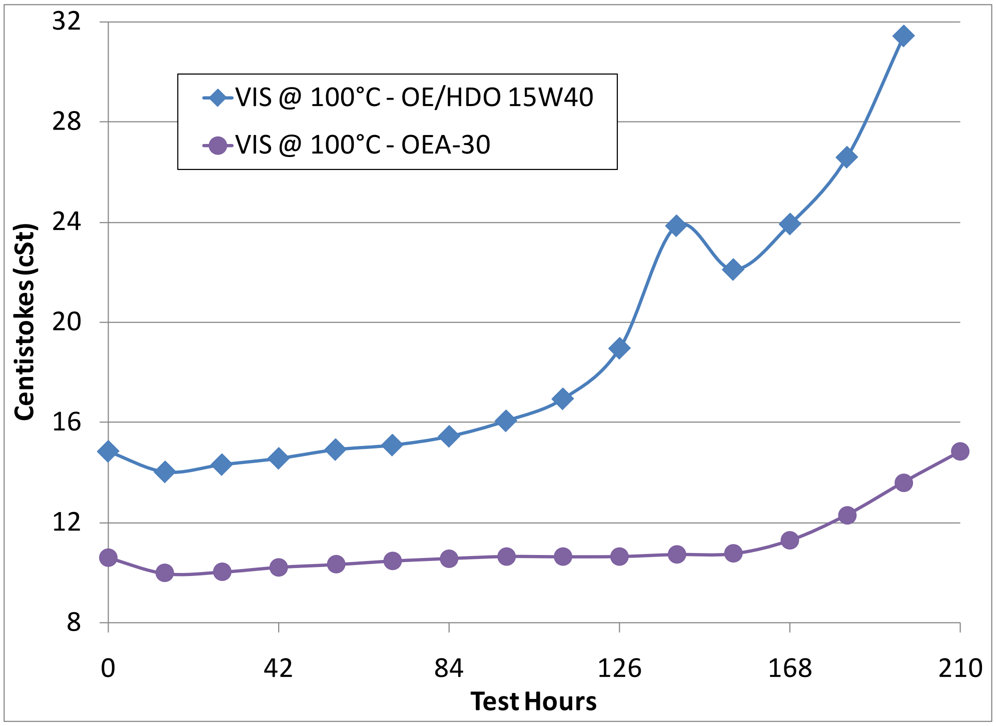

Figure 5. GEP 6.5L(T) Viscosity Response

From previous testing experience in the CAT C7 engine, following the standard 210 hour cycle there has been little discrimination between test oils. This is due to several reasons, including a larger oil sump capacity that reduces the stress experienced on the oil per unit volume. As a consequence, oil testing was scheduled for 2 times the standard 210 hour TWVC test length to operate the test long enough to observe actual changes in oil condition. The baseline oil was successfully run for a total of 420 testing hours with no major degradation in oil performance (Ref. 6). Testing was terminated at this point despite continued stable oil conditions due to the imminent crossing of the acid and base numbers. Similarly, the OEA-30 testing was initially scheduled to receive the same 420 hour test duration. Upon reaching this mark and observing the oil's overall condition, it was decided to continue testing. At 420 hours the OEA-30 oil still had a 1.5 point increase of base number over the acid number indicating the oils ability for continued use which showed improvement over the baseline test. At 630 hours, a full three times the normal test duration, the oil remained in good condition without any used oil properties indicating an imminent problem. Despite its continued stability, testing was then terminated so that post test engine inspection activities could be initiated. Figure 6 and 7, respectively, shows the TAN/TBN and viscosity response of the baseline and OEA-30 oil in the CAT C7 engine.

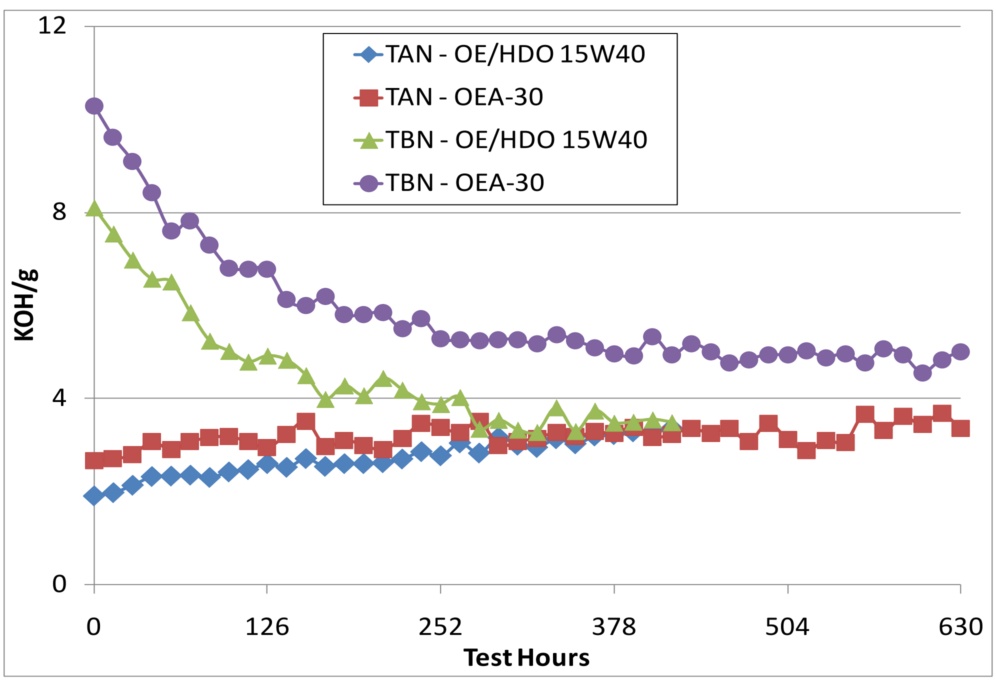

Figure 6. CAT C7 TAN/TBN Response

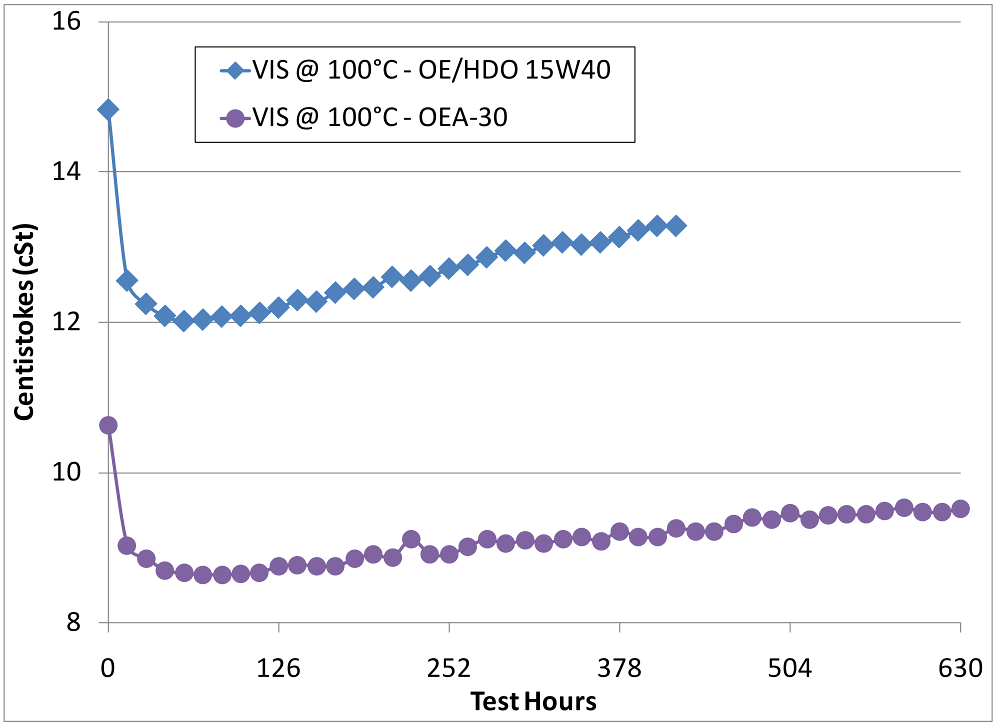

Figure 7. CAT C7 Viscosity Response

The baseline oil (OE/HDO15W40) test in the DDC Series 60 engine was conducted during a previous project (4). The OEA-30 test in the Series 60 engine was interrupted at 24 hours by a failure of the engine air compressor. The part was replaced; the engine crankcase was flushed thoroughly, and recharged with fresh OEA-30. The test was restarted and the oil completed 210 hours of testing, while the engine had accumulated 234 test hours. It should be noted that the OEA-30 oil used for this test only was manufactured by Emery Industries. Oil degradation in the DDC Series 60 engine was similar for both baseline and OEA-30 oil. Figures 8 and 9, respectively, show the TAN/TBN and viscosity response of the baseline and OEA-30 oil in the DDC Series 60 engine. The vertical hashed line in these figures shows the restart of the OEA-30 oil test. In Figure 8, the zero- hour used oil TAN/TBN values are questionable. The TAN is too high, and the TBN appears to be too low. Unfortunately, these used oil simples were not available for retest. The rest of the TAN/TBN values all look reasonable. Neither oil experienced rapid TAN increase during testing. The typical viscosity shear down of the baseline SAE 15W-40 can be seen in the first two data points of the baseline plot. Both oils retained consistent viscosity throughout testing.

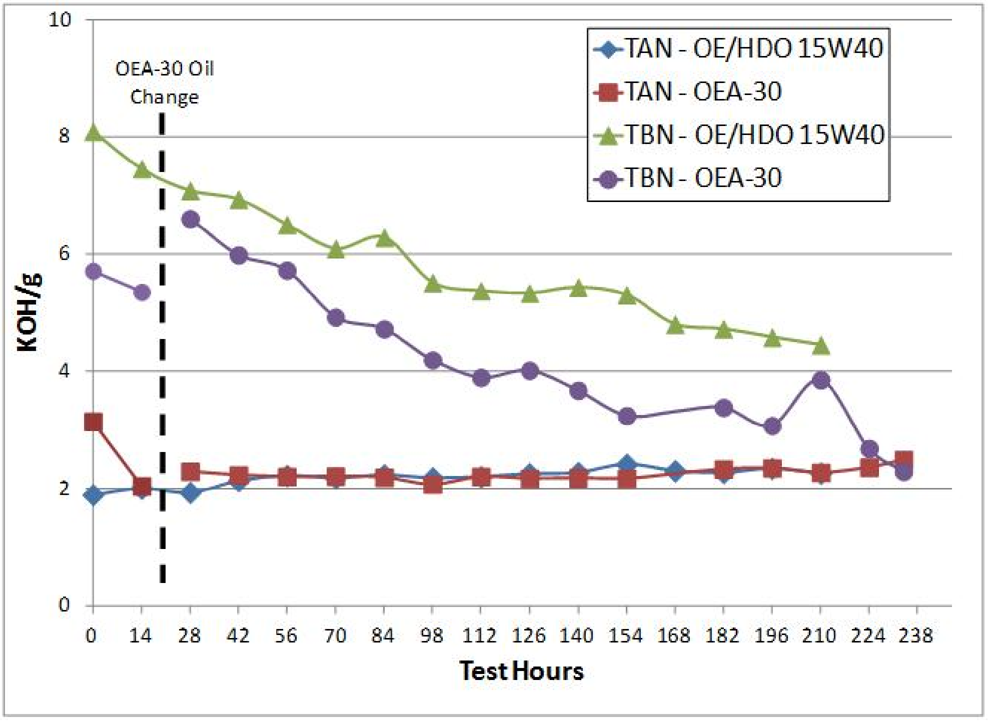

Figure 8. DDC Series 60 TAN/TBN Response

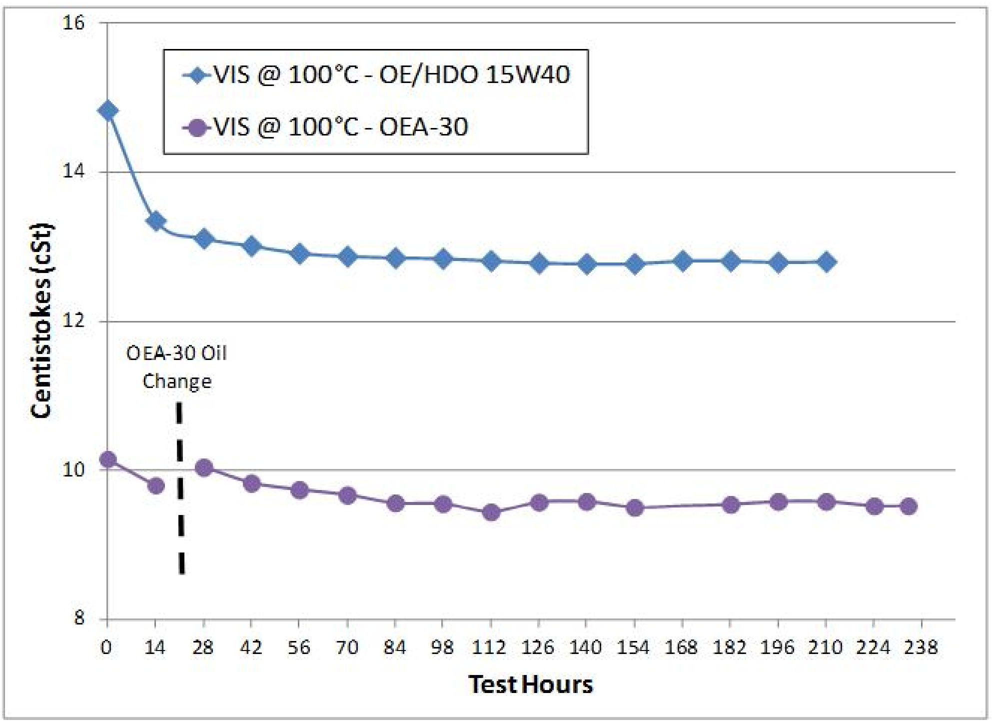

Figure 9. DDC Series 60 Viscosity Response

4.4 NATO Standard Engine Test Results

After observing positive results from the OEA-30 oil running the TWVC test, it was decided to run the NATO test to determine if oil degradation characteristics for the OEA-30 oil were similar to those experienced during the TWVC test. The NATO test was initially designed to be used to validate hardware performance for military applications, and thus is historically more severe on the tested hardware than the TWVC test. However, the rate of oil degradation remains consistent in the OEA-30 NATO testing, as was seen during the TWVC test.

When the OEA-30 NATO test was run on the GEP 6.5L(T) engine, oil changes were performed after every 100 hour segment by definition of the test procedure (denoted in each plot by a vertical line). This was not only required by the test procedure, but also needed due to the rate of oil degradation experienced during each 100 hours of testing. Figure 10 below shows the GEP 6.5L(T) viscosity response for the OEA-30 oil during the NATO test procedure.

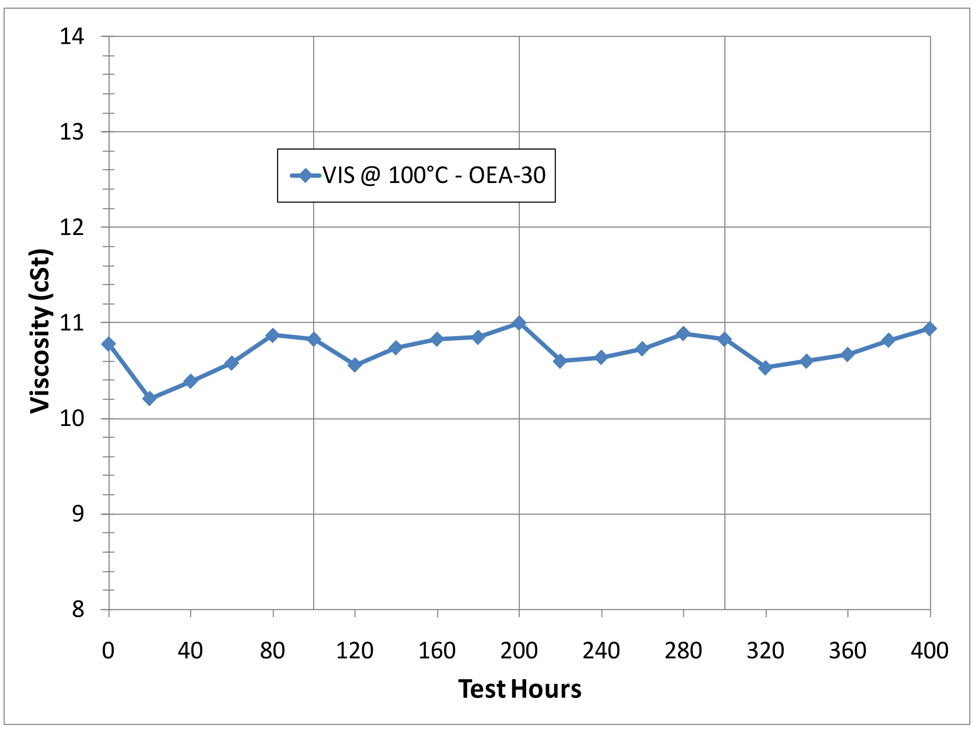

Figure 10. NATO Test GEP 6.5L(T) Viscosity Response

Figure 11 shows the TAN/TBN response of the GEP 6.5L(T) using the OEA-30 during NATO testing.

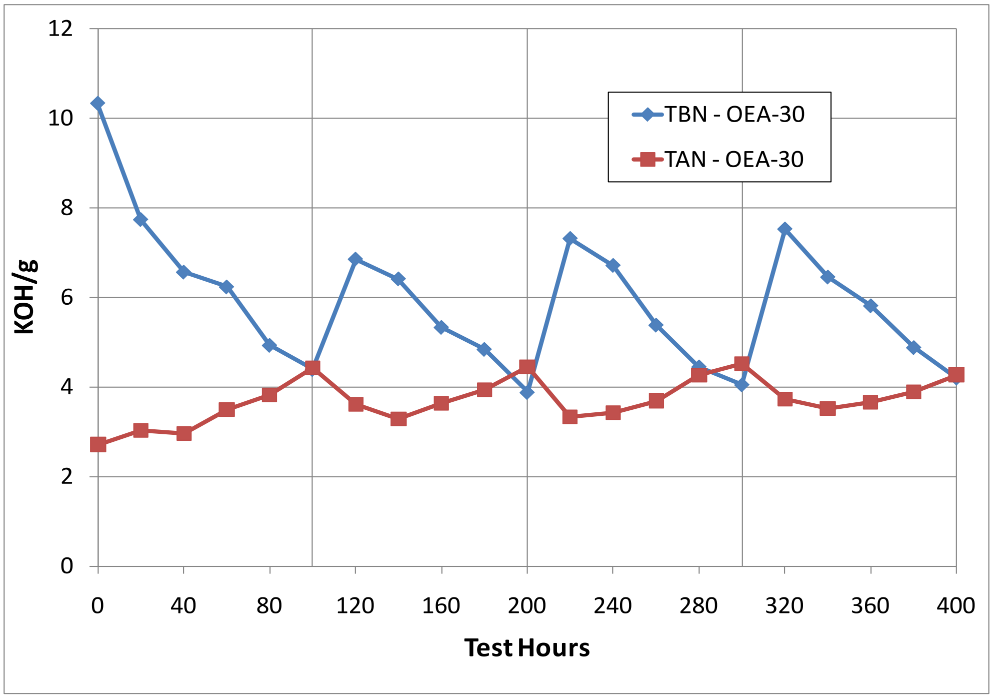

Figure 11. NATO Test GEP 6.5L(T) TAN/TBN Response

Figure 12 shows the accumulated wear metals for the GEP 6.5L(T) engine. This engine family typically generates high iron and copper wear metals. Note the reduction in iron (Fe) accumulation throughout testing as the engine continued to “break-in”.

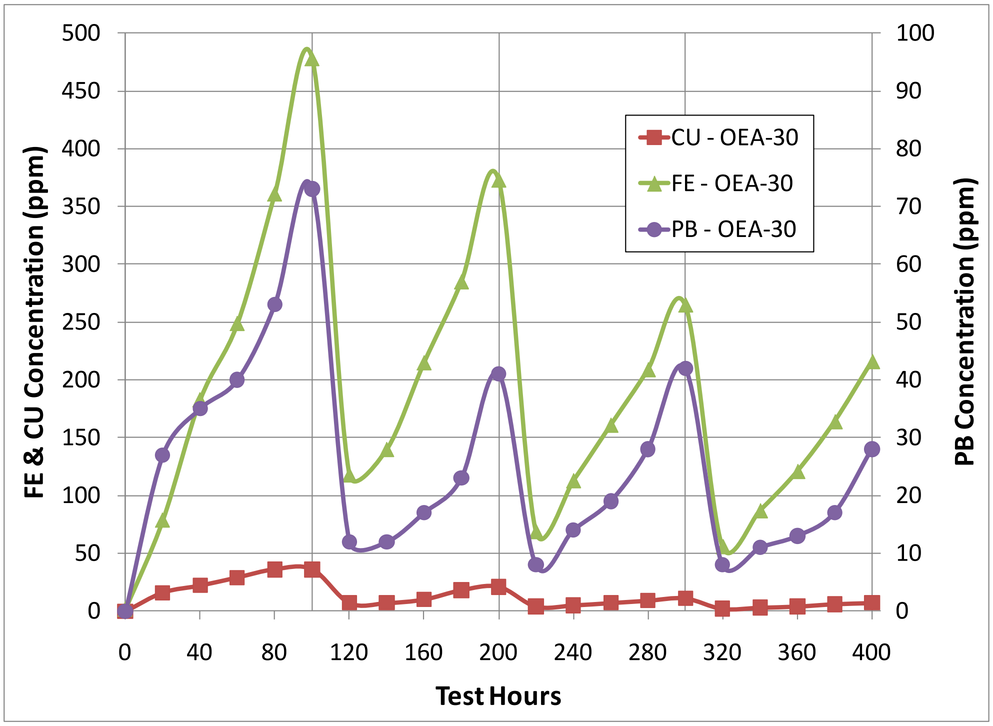

Figure 12. NATO Test GEP 6.5L(T) Accumulated Wear Metals

During the OEA-30 NATO testing on the CAT C7 engine, the same lack of major oil degradation as seen during the TWVC testing was also observed throughout the NATO test duration. Due to this, the CAT C7 engine completed the entire 400 hour test without any oil changes. Figure 13 shows the TAN/TBN response of the C7 engine using OEA-30 during NATO testing.

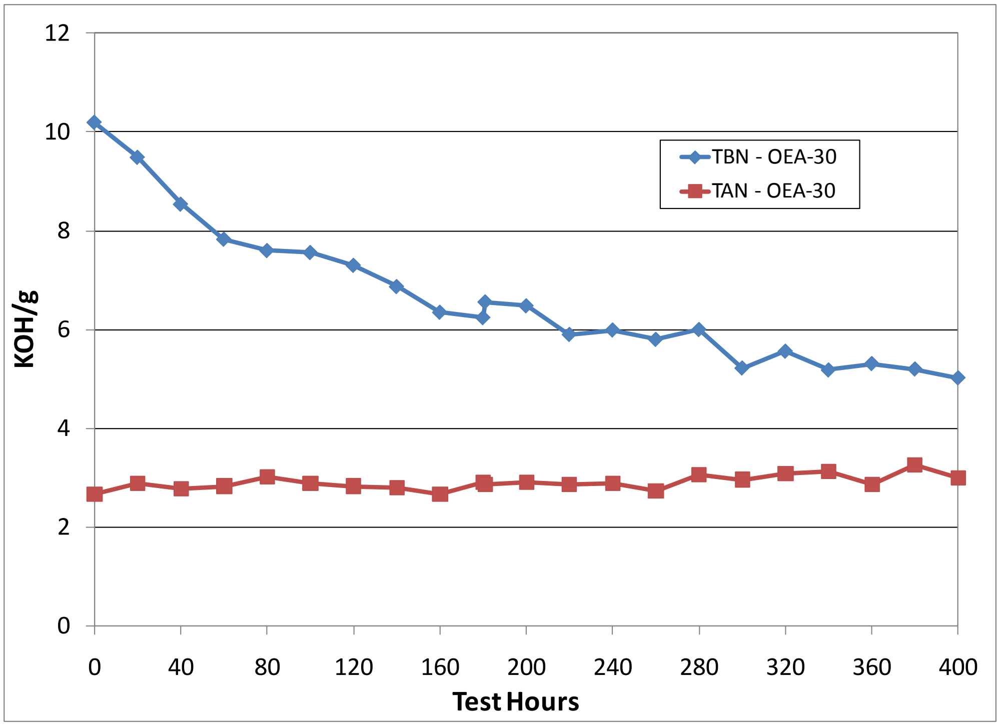

Figure 13. NATO Test CAT C7 TAN/TBN Response

5.0 SUMMARY/CONCLUSIONS

In particular, the use of lower viscosity oil formulations while maintaining adequate wear protection, was investigated. Engine dynamometer testing was conducted using three different engines common to the tactical fleet and representing light, medium, and heavy tactical service. Testing was conducted at elevated oil sump temperatures to simulate desert like conditions. It was found that a prototype SCPL (i.e., MIL-PRF-46167 OEA-30) provided equivalent or better wear protection than a standard MIL-PRF-2104G 15W-40 qualified product. It was also found that the OEA-30 had a substantially longer oil life.

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APPENDIX A

6.5L Turbocharged HMMWV

Test Number: LO228213-65T1-W-210

Test Procedure: Tactical Wheeled Vehicle

EVALUATION OF MIL-PRF-46167D OEA 0W-30 ARCTIC OIL

Work Directive No. 42

6.5L Turbocharged HMMWV

Test Lubricant: LO-228213
Experimental Arctic Oil – 0W30 OEA Lubrizol
Test Fuel: JP-8
Test Number: LO228213-65T1-W-210
Start of Test Date: January 13, 2009
End of Test Date: February 02, 2009
Test Duration: 210 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Introduction

This test was used to evaluate experimental arctic oil, Lubrizol OEA 0W30, for use in military tactical vehicles using the procedures outlined in the Tactical Wheeled Vehicle Cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Work Directive 42, Single Common Powertrain Lubricants for Combat/Tactical Equipment.

Test Engine

The experimental oil was evaluated in the General Engine Products (GEP) 6.5L turbocharged diesel engine, representative of engines currently fielded in High Mobility Multipurpose Wheeled Vehicles (HMMWV). Prior to testing, the engine was disassembled and measured for pre-test wear. Engine clearances and specifications were verified, and the engine was reassembled following standard assembly procedures.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for GEP engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorbing dynamometer was used to supply engine loading. Engine oil, fuel, and coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers. Engine intake air was supplied at ambient conditions, with its flowrate measured using pressure drop across a laminar flow element (LFE).

Engine Run-in

Prior to testing, the engine was run-in using the candidate oil following procedures outlined below. Cyclic modes were repeated for a total of 24 cycles. Total runtime for engine run-in was approximately 6 hours.

Time, min	Mode	Speed, RPM	Torque, lb*ft	Coolant Out, °F	Oil Galley, °F
10	Steady State	1500	10	215	220
10	Steady State	1600	109	215	220
10	Steady State	2400	145	215	220
10	Steady State	3200	165	215	220
1	Cyclic	900	0	215	220
2	Cyclic	2600	50%	215	220
2	Cyclic	1800	1%	215	220
2	Cyclic	1200	25%	215	220
2	Cyclic	1800	50%	215	220
2	Cyclic	3200	5%	215	220
2	Cyclic	2200	50%	215	220

Figure 1 - Test Engine Run-In Procedure

Pre-Test Engine Performance Check

After completion of engine run-in, a full load powercurve was completed from 1000 rpm to rated engine speed (3200 rpm) to determine pre-test engine performance. The pre-test engine performance check was completed using the same oil charge used during the engine run-in segment. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during oil evaluation was the standard 210 hr Tactical Wheeled Vehicle cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Test termination would occur at 210 hrs or upon major oil degradation, which ever occurred first. The test cycle consists of cyclic modes alternating between 2 hr rated speed conditions and 1 hr idle soaks. Total daily run-time was 14 hrs, 10 hrs at rated and 4 hrs at idle, with a 10 hr soak overnight before resuming the next days testing. Engine oil and coolant temperatures were elevated to simulate conditions consistent with desert warfare use. Engine operating parameters were controlled through out testing as specified in the table below.

Parameter	Rated Speed	Idle
Engine Speed, RPM	3200 +/- 25	900 +/- 25
Water Jacket Out, °F	206 +/- 3	100 +/- 3
Oil Sump, °F	263 +/- 3	125 +/- 3

Figure 2 - Test Cycle Operating Parameters

Engine coolant was a 60/40 blend of ethylene glycol antifreeze and deionized water. Test fuel was JP-8.

Oil Sampling

Eight ounces of engine oil was sampled every 14 hrs for used oil analysis. Engine oil analysis consisted of the following tests: (Note – at every 70 hr interval, two additional tests were completed on the used oil as shown below). All oil samples were weighed and logged to take into account during calculations of total engine oil consumption for the test duration.

Every 14hrs		
ASTM	**D4739**	Total Base Number
ASTM	**D664**	Total Acid Number
ASTM	**D445**	Kinematic Viscosity @ 100°C
ASTM	**API Gravity**	API Gravity
ASTM	**D4052**	Density
ASTM	**TGA SOOT**	TGA Soot
ASTM	**E168**	Oxidation
ASTM	**E168**	Nitration
ASTM	**D5185**	Wear Metals by ICP

Every 70hrs		
ASTM	**D445**	Kinematic Viscosity @ 40°C
ASTM	**D2270**	Kinematic Viscosity Index

Figure 3 - Used Oil Analysis Procedures

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily and replenished as needed to restore oil level to the full mark. This process occurred daily after the completion of the 10 hr soak prior to restarting testing the next day. All oil additions were weighed and logged to take into account during calculation of total engine oil consumption for the test duration.

Post-Test Engine Performance Check

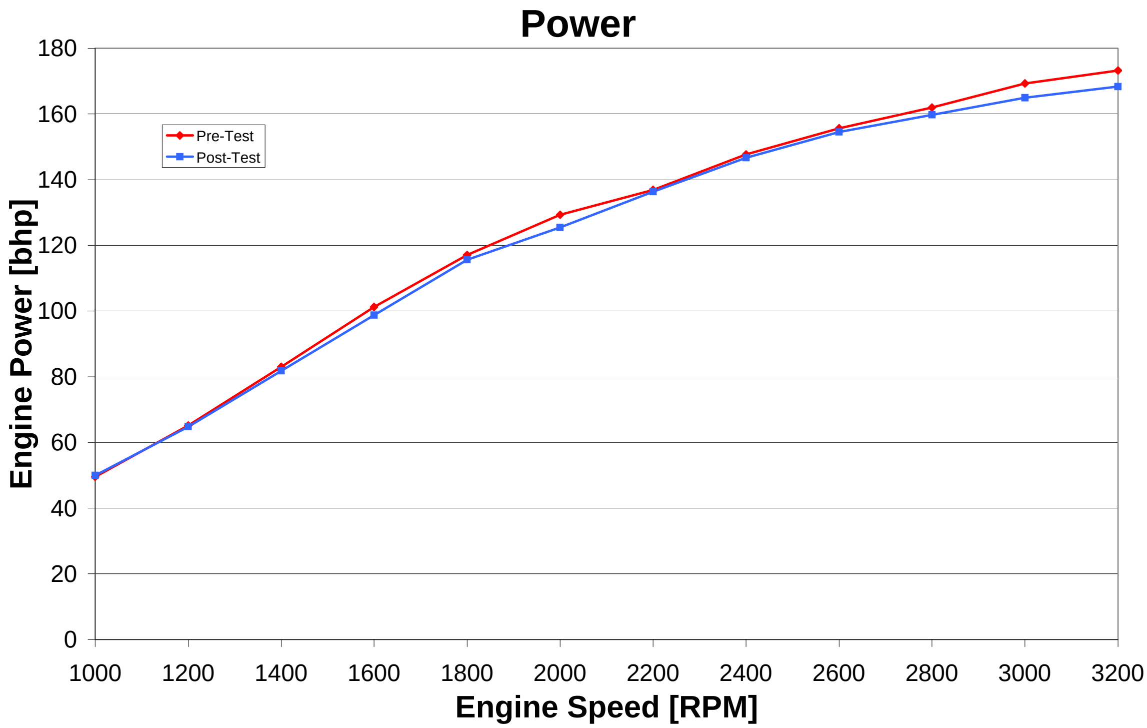
After completion of testing, a full load powercurve was completed from 1000 rpm to rated engine speed (3200 rpm) to determine post-test engine performance. The post-test engine performance check was completed using the same oil charge used during the testing segment. Powercurve plots can be seen in the Engine Performance Curves section.

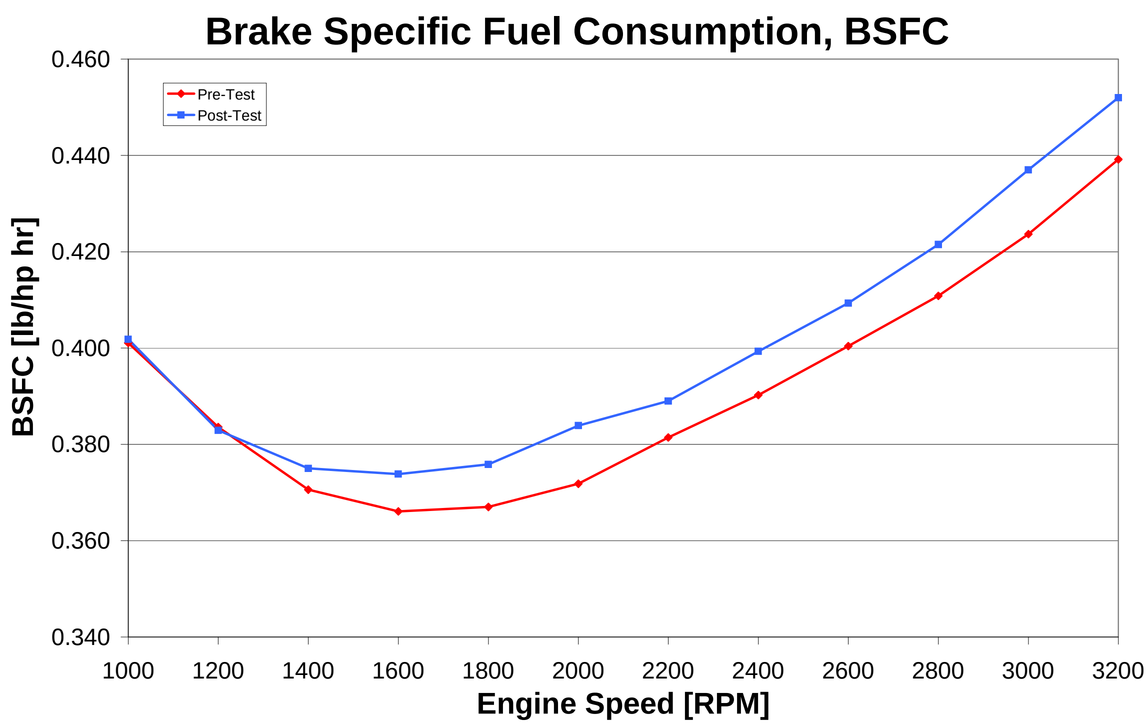
Engine Operating Conditions Summary

Below is a summary of the engine operating conditions over the duration of the 210 engine running hours.

		Rated Conditions *(3200 RPM)*		**Idle Conditions** *(900 RPM)*	
Perameter:	**Units:**	Average	Std. Dev.	Average	Std. Dev.
Engine Speed	*RPM*	3200	1.1	900	5.4
Torque	*ft*lb*	283.6	4.7	3.4	0.8
Fuel Flow	*lb/hr*	75.7	0.9	3.9	0.1
Power	*bhp*	172.8	2.9	0.6	0.1
BSFC	*lb/bhp*hr*	0.438	0.005	6.879	1.664
Temperatures:					
Coolant In	*°F*	192.0	0.8	93.6	1.1
Coolant Out	*°F*	205.9	0.7	99.8	0.9
Oil Sump	*°F*	263.0	0.8	124.5	2.2
Fuel In	*°F*	98.3	6.5	94.6	6.1
Intake Air	*°F*	84.0	6.5	72.5	6.8
Cylinder 1 Exhaust	*°F*	1140.9	11.2	163.1	6.3
Cylinder 2 Exhaust	*°F*	1165.3	7.8	146.7	8.5
Cylinder 3 Exhaust	*°F*	1172.0	9.3	150.2	6.8
Cylinder 4 Exhaust	*°F*	1162.8	8.9	157.3	6.4
Cylinder 5 Exhaust	*°F*	1136.6	7.6	152.2	6.5
Cylinder 6 Exhaust	*°F*	1142.2	8.7	154.0	7.0
Cylinder 7 Exhaust	*°F*	1122.9	9.7	143.6	4.5
Cylinder 8 Exhaust	*°F*	1141.5	8.7	141.6	6.5
Pressures:					
Oil Galley	*psi*	33.4	0.6	35.3	3.3
Ambient Pressure	*psiA*	14.4	0.1	14.5	0.1
Boost Pressure	*psi*	18.5	0.3	14.4	0.2

Engine Performance Curves

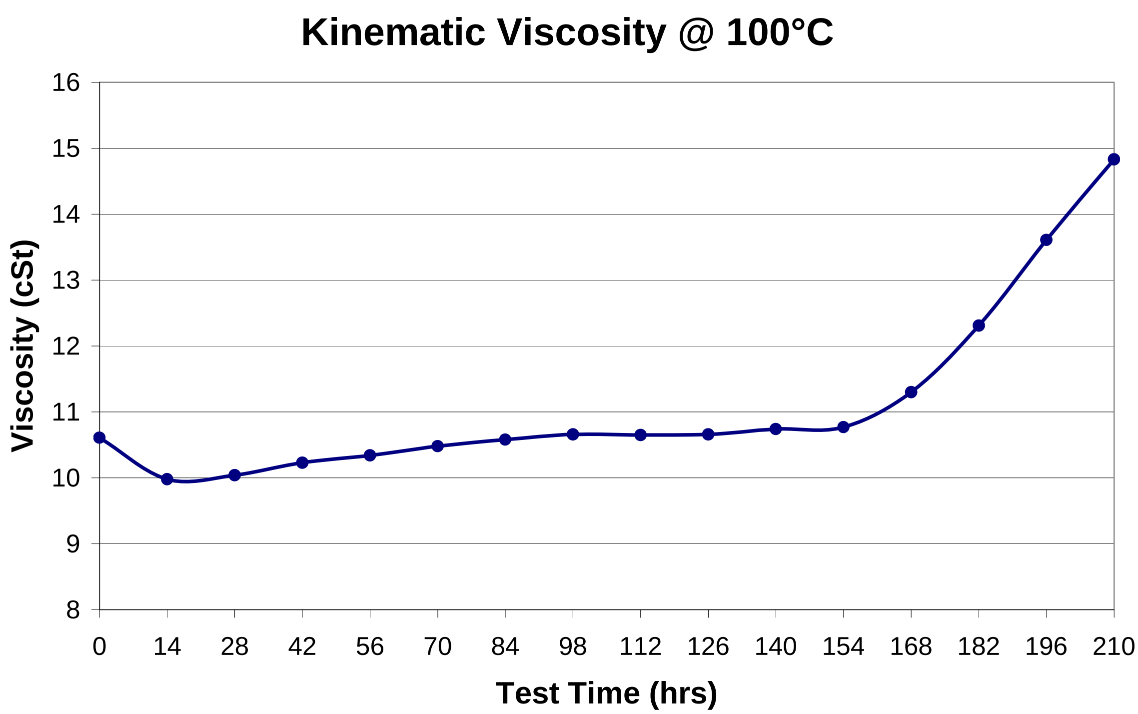


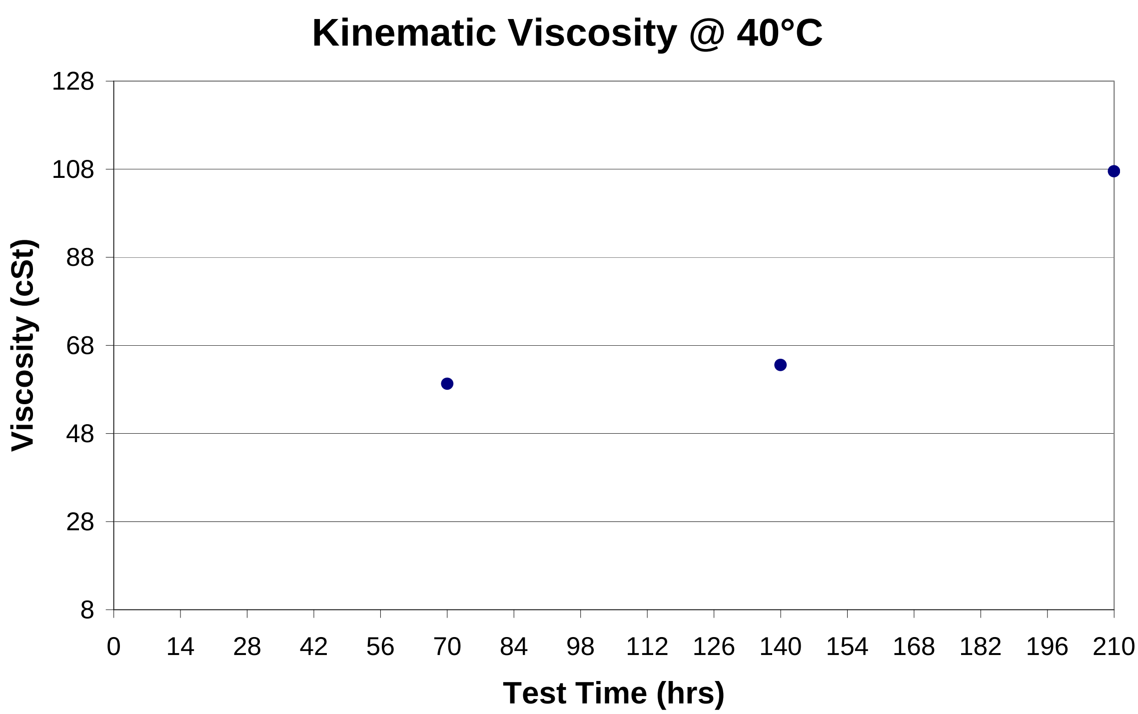


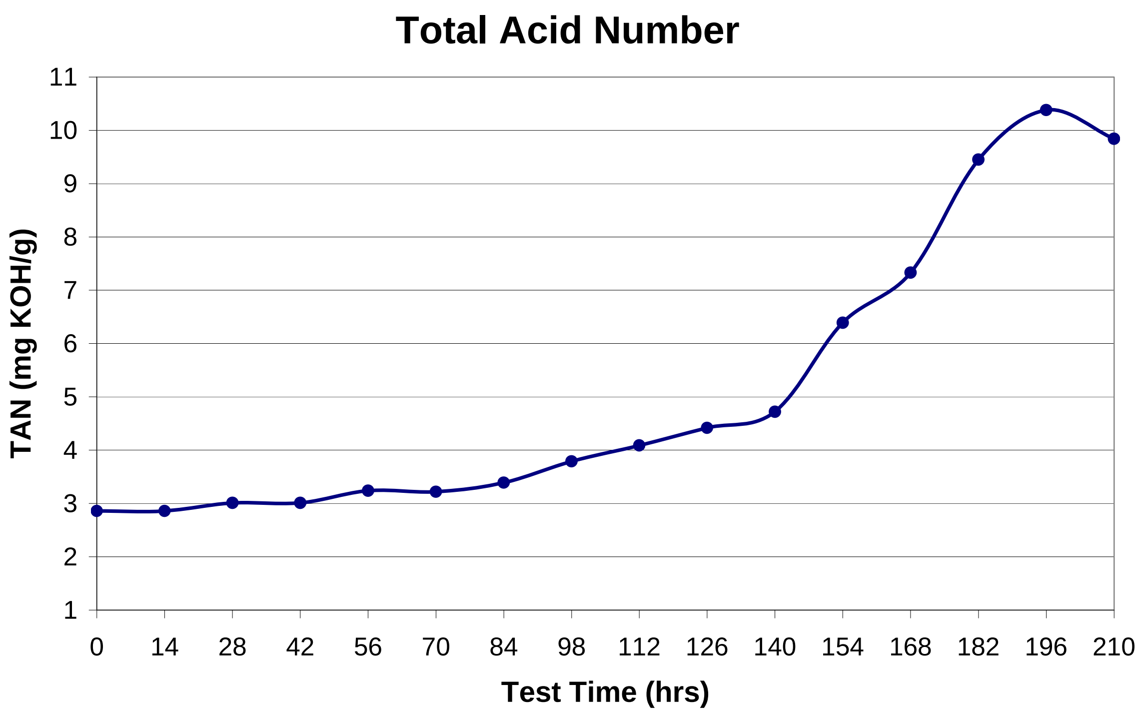
Engine Oil Analysis

Property	ASTM Test No.	Test Hours															
		0	**14**	**28**	**42**	**56**	**70**	**84**	**98**	**112**	**126**	**140**	**154**	**168**	**182**	**196**	**210**
Density (g/ml)	**D4052**	0.8493	0.8515	0.8539	0.856	0.8579	0.8601	0.8614	0.8634	0.8657	0.8687	0.8715	0.8771	0.8854	0.8957	0.9013	0.9037
Viscosity @ 100°C (cSt)	**D445**	10.61	9.98	10.04	10.23	10.34	10.48	10.58	10.66	10.65	10.66	10.74	10.77	11.3	12.31	13.61	14.83
Viscosity @ 40°C (cSt)	**D445**						59.29					63.56					107.53
Viscosity Index (dyne/cm)	**D2270**						168					160					143
Total Base Number (mg KOH/g)	**D4739**	10.31	8.2	7.2	6.87	5.76	5.7	5.6	5.13	4.53	3.93	3.69	3.07	2.72	1.79	1.72	2.2
Total Acid Number (mg KOH/g)	**D664**	2.86	2.86	3.01	3.01	3.24	3.22	3.39	3.79	4.09	4.42	4.72	6.39	7.33	9.45	10.38	9.84
Oxidation (Abs/cm)	**E168 FTNG**	0	2.31	7.49	11.37	14.42	18.58	20.98	24.86	29.94	36.88	47.32	60.35	90.94	129.21	141.59	141.68
Nitration (Abs/cm)	**E168 FTNG**	0	2.4	2.4	2.31	2.5	4.99	4.71	6.84	10.26	15.53	19.32	30.59	39.19	42.7	39.65	31.52
Soot (TGA)	**Soot**	0.11	0.355	0.486	0.722	0.918	1.086	1.114	1.238	1.43	1.709	1.829	2.184	2.333	2.677	3.041	3.261
Wear Metals by ICP (ppm)	**D5185**																
Al		1	3	5	6	6	7	7	7	8	9	11	12	12	13	15	17
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		3	3	4	4	4	4	2	5	4	5	8	6	5	5	4	4
Ca		3544	3692	3856	3922	4083	4173	4139	4221	4287	4606	4504	4682	4798	4924	5142	5376
Cr		<1	2	4	5	7	8	9	9	10	11	13	14	15	16	18	19
Cu		<1	40	47	48	50	54	53	52	56	57	56	60	75	144	300	475
Fe		2	74	131	175	207	246	259	284	315	371	390	454	544	669	831	986
Pb		<1	11	14	15	15	17	17	20	26	38	55	101	259	771	1352	1679
Mg		14	15	16	17	17	17	18	17	21	20	19	21	20	22	23	23
Mn		<1	2	2	3	4	4	4	4	5	5	5	6	7	8	9	10
Mo		<1	10	19	24	27	32	32	33	34	37	40	44	46	50	55	60
Ni		<1	2	4	5	6	7	8	8	8	9	10	11	12	13	14	16
P		1340	1231	1219	1202	1217	1254	1275	1268	1330	1364	1397	1434	1422	1494	1572	1617
Si		4	7	9	9	10	11	10	11	11	12	13	14	13	14	14	19
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	6	5	<5	5	5	6	<5	6	6	7	6	<5	7	8	8
Sn		<1	10	13	14	16	16	16	16	17	19	21	22	25	29	36	40
Zn		1469	1484	1474	1504	1590	1635	1644	1634	1719	1771	1805	1850	1924	2033	2112	2098
K		10	5	<5	<5	<5	5	<5	<5	<5	5	<5	<5	<5	<5	<5	<5
Sr		<1	<1	<1	<1	1	1	1	1	<1	<1	<1	<1	1	1	1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Engine Oil Analysis Trends



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TAN (mg KOH/g)
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10
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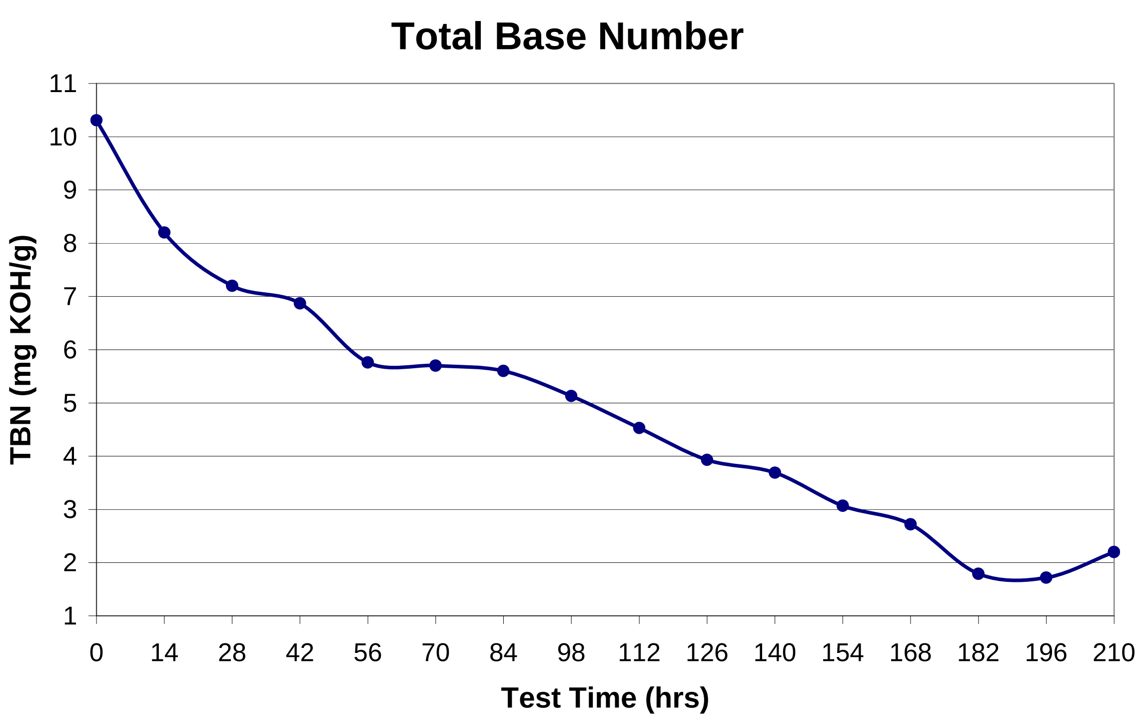
182
196
210
Test Time (hrs)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TBN (mg KOH/g)
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84
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112
126
140
154
168
182
196
210
Test Time (hrs)


Soot
(%)
0
1
2
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140
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168
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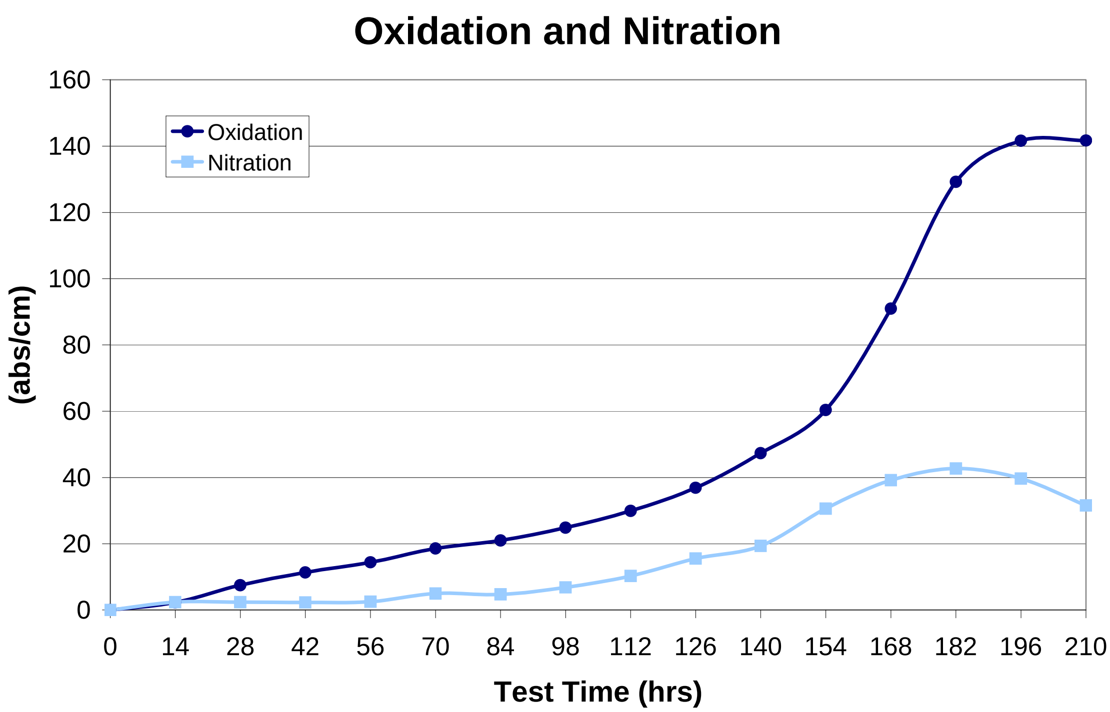
196
210
Test Time (hrs)


Oxidation and Nitration
(abs/cm)
Oxidation
Nitration
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20
40
60
80
100
120
140
160
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14
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42
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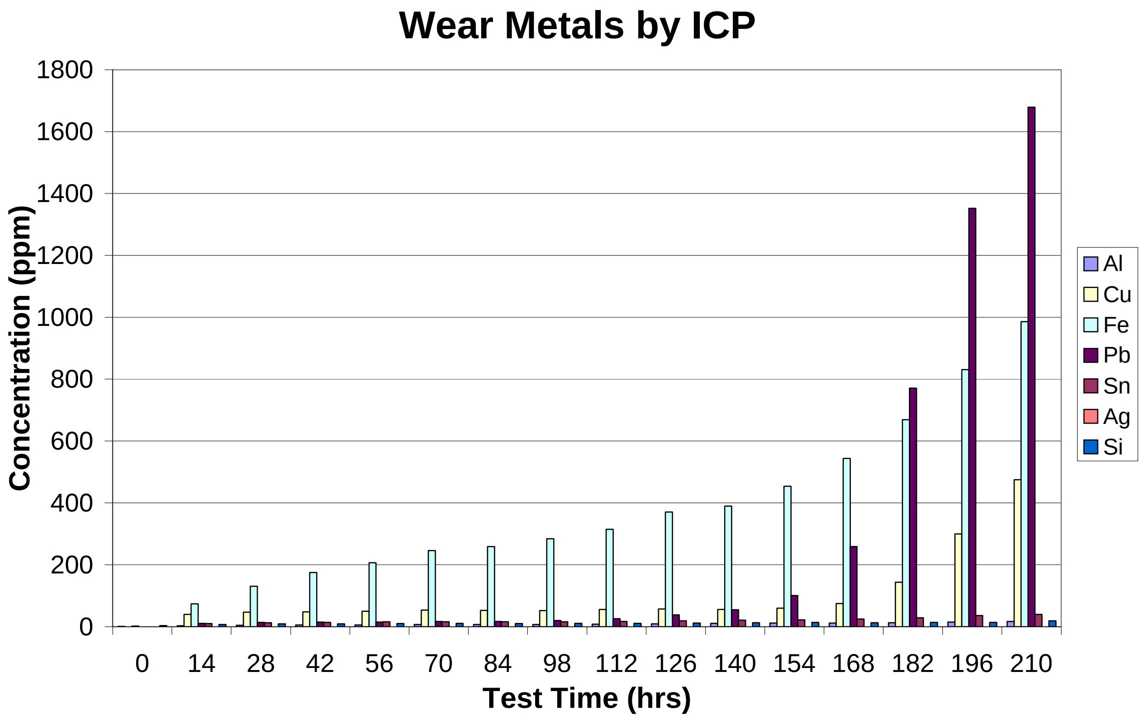
196
210
Test Time (hrs)



Oil Consumption Data

Average oil consumption per test hour was 0.092 lbs/hr.

	Additions (lbs)	Samples (lbs)	Consumption (lbs)	Consumption Accumulated
14-hr	0	0.43	*-0.43*	*-0.43*
28-hr	1.73	0.41	1.32	0.89
42-hr	1.88	0.4	1.48	2.37
56-hr	1.47	0.41	1.06	3.43
70-hr	1.75	0.41	1.34	4.77
84-hr	1.57	0.42	1.15	5.92
98-hr	1.48	0.41	1.07	6.99
112-hr	1.33	0.55	0.78	7.77
126-hr	1.71	0.41	1.3	9.07
140-hr	1.16	0.42	0.74	9.81
154-hr	1.43	0.41	1.02	10.83
168-hr	1.63	0.42	1.21	12.04
182-hr	1.75	0.42	1.33	13.37
196-hr	1.75	0.41	1.34	14.71
210-hr	4.94	0.43	4.51	19.22
	Initial Fill	14.86	**Total Additions**	25.58
	EOT Drain	14.32	**Total Samples**	6.36

(Initial Fill + Additions)	40.44
(EOT Drain + Samples)	20.68
Total Oil Consumption	19.76

Post Test Engine Ratings

Ratings	Clyinder Number								
	1	2	3	4	5	6	7	8	Avg
Ring Sticking									
Ring No.1	No	No	No	No	No	No	No	No	--
Ring No.2	No	No	No	No	No	No	No	No	--
Ring No.3	No	No	No	No	No	No	No	No	--
Scuffing % Area									
Ring No.1	0	0	0	0	0	0	0	0	0.00
Ring No.2	0	0	0	0	0	0	0	0	0.00
Ring No.3	0	0	0	0	0	0	0	0	0.00
Piston Crown	0	0	0	0	0	0	0	0	0.00
Piston Skirt	0	0	0	0	0	0	0	0	0.00
Cylinder Liner, %	15	5	5	10	10	10	10	5	8.75
Piston Carbon, Demerits									
No.1 Groove	72.50	58.75	85.00	69.75	86.00	52.75	77.25	65.00	70.88
No.2 Groove	18.25	7.25	28.75	5.75	12.75	2.50	7.25	25.00	13.44
No.3 Groove	--	--	--	--	--	--	--	--	
No.1 Land	43.00	45.25	33.00	55.50	38.00	44.75	34.25	39.50	41.66
No.2 Land	43.00	25.00	43.50	28.00	34.75	19.00	29.25	39.50	32.75
No.3 Land	24.00	6.75	6.00	2.25	1.50	--	1.25	3.00	6.39
Upper Skirt	--	--	--	--	--	--	--	--	--
Under Crown	--	--	--	--	--	--	--	--	--
Front Pin Bore	--	--	--	--	--	--	--	--	--
Rear Pin Bore	--	--	--	--	--	--	--	--	--
Piston Lacquer, Demerits									
No.1 Groove	--	0.90	--	0.45	--	--	--	--	0.68
No.2 Groove	0.62	2.82	--	1.95	4.12	3.49	2.61	--	2.60
No.3 Groove	2.27	2.48	2.97	2.10	2.61	2.50	2.38	2.30	2.45
No.1 Land	--	0.33	0.57	0.28	0.01	0.09	0.55	0.01	0.26
No.2 Land	0.15	1.20	0.20	0.22	0.38	1.14	0.47	0.19	0.49
No.3 Land	0.12	2.15	2.03	2.12	2.85	2.43	3.80	2.26	2.22
Upper Skirt	0.62	0.65	0.77	0.77	0.77	0.77	0.94	1.14	0.80
Under Crown	1.58	2.45	1.63	2.61	2.08	2.02	2.25	2.25	2.11
Front Pin Bore	3.10	3.48	3.60	3.30	3.80	4.50	3.80	3.80	3.67
Rear Pin Bore	3.10	3.48	3.60	3.30	3.80	4.00	3.80	3.80	3.61
Total, Demerits	212.31	162.94	211.62	178.35	193.42	139.94	169.85	187.75	182.02
Miscellanous									
Top Groove Fill, %	60	47	85	67	82	44	89	58	66.50
Intermediate Groove Fill, %	11	4	13	10	4	1	7	20	8.75
Top Land Heavy Carbon, %	24	29	14	42	18	27	16	20	23.75
Top Lan Flaked Carbon, %	0	0	0	0	0	0	0	0	0.00
Valve Tulip Deposits, Merits									
Exahust	9.6	9.5	9.1	9.7	9.1	9.1	9.5	9.1	9.34
Intake	9.2	6.4	6.0	6.0	6.0	6.0	6.1	6.5	6.53

Engine Measurement Changes

Engine Rebuild Measurements, inches

Cylinder Bore	Minimum	Maximum	Average	Spec:
Inside Diameter	4.0547	4.0555	4.0549	Cylinder 1 thru 6 ID 4.054"-4.075" Cylinder 7 thru 8 ID 4.055"-4.076"
Out of Round	0.0000	0.0009	0.0004	Maximum 0.008"
Taper	0.0001	0.0009	0.0005	
Piston Skirt Diameter	4.0495	4.0500	4.0497	
Piston Skirt to Cylinder Bore Clearance	0.0051	0.0055	0.0052	Cylinder 1 thru 7 0.003"-0.004" Cylinder 7 thru 8 0.004"-0.005"
Piston Ring End Gaps				
Top Ring	0.020	0.022	0.022	
Second Ring	0.038	0.040	0.039	
Oil Control Ring	0.022	0.024	0.023	
Ring To Groove Clearance				
Second Ring	0.0015	0.0015	0.0015	0.0015"-0.003"
Oil Control Ring	0.0015	0.0015	0.0015	0.0015"-0.0035"
Piston Pin				
Piston Pin Diameter	1.2203	1.2203	1.2203	1.2203"-1.2206"
Piston Bore Diameter	1.2213	1.2216	1.2215	1.2207"-1.2212"
Piston Pin Clearance	0.0010	0.0013	0.0012	0.0003"-0.0012"
Bearing Clearances				
Connecting Rod to Journal	0.002	0.002	0.002	0.0017"-0.0039"
Main Bearing to Journa	0.002	0.002	0.002	0.001"-0.005"

Pre-Test Cylinder Bore Measurements, inches

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.0552	4.0546		0.0006
	Middle	4.0549	4.0540	4.0549	0.0009
	Bottom	4.0548	4.0546		0.0002
	Taper	0.0004	0.0006		
2	Top	4.0549	4.0548		0.0001
	Middle	4.0550	4.0544	4.0550	0.0006
	Bottom	4.0550	4.0548		0.0002
	Taper	0.0001	0.0004		
3	Top	4.0554	4.0546		0.0008
	Middle	4.0548	4.0542	4.0547	0.0006
	Bottom	4.0545	4.0546		0.0001
	Taper	0.0009	0.0004		
4	Top	4.0552	4.0548		0.0004
	Middle	4.0550	4.0550	4.0548	0.0000
	Bottom	4.0546	4.0548		0.0002
	Taper	0.0006	0.0002		
5	Top	4.0554	4.0546		0.0008
	Middle	4.0548	4.0542	4.0547	0.0006
	Bottom	4.0545	4.0547		0.0002
	Taper	0.0009	0.0005		
6	Top	4.0549	4.0546		0.0003
	Middle	4.0550	4.0548	4.0549	0.0002
	Bottom	4.0548	4.0548		0.0000
	Taper	0.0002	0.0002		
7	Top	4.0556	4.0553		0.0003
	Middle	4.0553	4.0549	4.0552	0.0004
	Bottom	4.0551	4.0551		0.0000
	Taper	0.0005	0.0004		
8	Top	4.0558	4.0556		0.0002
	Middle	4.0555	4.0548	4.0555	0.0007
	Bottom	4.0554	4.0551		0.0003
	Taper	0.0004	0.0008		

Post-Test Cylinder Bore Measurements, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.0547	4.0551		0.0004
	Middle	4.0551	4.0564	4.0552	0.0013
	Bottom	4.0552	4.0561		0.0009
	Taper	0.0005	0.0013		
2	Top	4.0548	4.0555		0.0007
	Middle	4.0550	4.0563	4.0551	0.0013
	Bottom	4.0551	4.0559		0.0008
	Taper	0.0003	0.0008		
3	Top	4.0544	4.0551		0.0007
	Middle	4.0549	4.0564	4.0549	0.0015
	Bottom	4.0549	4.0561		0.0012
	Taper	0.0005	0.0013		
4	Top	4.0547	4.0557		0.0010
	Middle	4.0550	4.0565	4.0551	0.0015
	Bottom	4.0551	4.0561		0.0010
	Taper	0.0004	0.0008		
5	Top	4.0544	4.0552		0.0008
	Middle	4.0548	4.0564	4.0549	0.0016
	Bottom	4.0550	4.0561		0.0011
	Taper	0.0006	0.0012		
6	Top	4.0547	4.0554		0.0007
	Middle	4.0550	4.0563	4.0551	0.0013
	Bottom	4.0551	4.0560		0.0009
	Taper	0.0004	0.0009		
7	Top	4.0544	4.0549		0.0005
	Middle	4.0547	4.0557	4.0547	0.0010
	Bottom	4.0547	4.0555		0.0008
	Taper	0.0003	0.0008		
8	Top	4.0546	4.0550		0.0004
	Middle	4.0548	4.0559	4.0548	0.0011
	Bottom	4.0548	4.0557		0.0009
	Taper	0.0002	0.0009		

Cylinder Bore Diameter Changes, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. Change (TD@MID + TD@BOT)/2
1	Top	0.0005	0.0005	
	Middle	0.0002	0.0024	0.0003
	Bottom	0.0004	0.0015	
2	Top	0.0001	0.0007	
	Middle	0.0000	0.0019	0.0001
	Bottom	0.0001	0.0011	
3	Top	0.0010	0.0005	
	Middle	0.0001	0.0022	0.0002
	Bottom	0.0004	0.0015	
4	Top	0.0005	0.0009	
	Middle	0.0000	0.0015	0.0003
	Bottom	0.0005	0.0013	
5	Top	0.0010	0.0006	
	Middle	0.0000	0.0022	0.0002
	Bottom	0.0005	0.0014	
6	Top	0.0002	0.0008	
	Middle	0.0000	0.0015	0.0002
	Bottom	0.0003	0.0012	
7	Top	0.0012	0.0004	
	Middle	0.0006	0.0008	0.0005
	Bottom	0.0004	0.0004	
8	Top	0.0012	0.0006	
	Middle	0.0007	0.0011	0.0006
	Bottom	0.0006	0.0006	
Avgerage All Cylinders	Top	0.0007	0.0006	
	Middle	0.0002	0.0017	
	Bottom	0.0004	0.0011	

Piston Skirt to Bore Clearance, in

	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
Pre - Test	1	4.0549	4.0496	0.0053
	2	4.0550	4.0497	0.0053
	3	4.0547	4.0495	0.0052
	4	4.0548	4.0496	0.0052
	5	4.0547	4.0496	0.0051
	6	4.0549	4.0497	0.0052
	7	4.0552	4.0500	0.0052
	8	4.0555	4.0500	0.0055
Post - Test	1	4.0552	4.0496	0.0056
	2	4.0551	4.0496	0.0054
	3	4.0549	4.0495	0.0054
	4	4.0551	4.0496	0.0054
	5	4.0549	4.0495	0.0054
	6	4.0551	4.0497	0.0053
	7	4.0547	4.0500	0.0047
	8	4.0548	4.0500	0.0048

Top and Second Ring Radial Wear, in

Top Ring				
Cylinder	Position	Before	After	Delta
1	1	0.17865	0.17635	0.00230
	2	0.17790	0.17695	0.00095
	3	0.17830	0.17735	0.00095
	4	0.17920	0.17815	0.00105
	5	0.17865	0.17735	0.00130
2	1	0.17900	0.17860	0.00040
	2	0.17905	0.17880	0.00025
	3	0.17950	0.17915	0.00035
	4	0.17065	0.18015	*-0.00950*
	5	0.17905	0.17845	0.00060
3	1	0.17850	0.17725	0.00125
	2	0.17815	0.17675	0.00140
	3	0.17915	0.17735	0.00180
	4	0.18035	0.17900	0.00135
	5	0.17945	0.17735	0.00210
4	1	0.17850	0.17755	0.00095
	2	0.17985	0.17930	0.00055
	3	0.17905	0.17860	0.00045
	4	0.17705	0.17645	0.00060
	5	0.17710	0.17690	0.00020
5	1	0.17930	0.17655	0.00275
	2	0.17975	0.17740	0.00235
	3	0.17765	0.17520	0.00245
	4	0.17690	0.17470	0.00220
	5	0.17875	0.17635	0.00240
6	1	0.17955	0.17905	0.00050
	2	0.17970	0.17880	0.00090
	3	0.17790	0.17725	0.00065
	4	0.17900	0.17825	0.00075
	5	0.17905	0.17855	0.00050
7	1	0.17945	0.17875	0.00070
	2	0.17955	0.17920	0.00035
	3	0.17940	0.17900	0.00040
	4	0.17865	0.17835	0.00030
	5	0.17870	0.17860	0.00010
8	1	0.17880	0.17875	0.00005
	2	0.17895	0.17785	0.00110
	3	0.17800	0.17755	0.00045
	4	0.18085	0.17980	0.00105
	5	0.17950	0.17900	0.00050
***Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error**				

Maximum	0.00275
Average	0.00074

Second Ring				
Cylinder	Position	Before	After	Delta
1	1	0.16100	0.15995	0.00105
	2	0.16115	0.16055	0.00060
	3	0.16115	0.16045	0.00070
	4	0.16075	0.15995	0.00080
	5	0.16025	0.15985	0.00040
2	1	0.16075	0.16290	*-0.00215*
	2	0.16115	0.16275	*-0.00160*
	3	0.16110	0.16250	*-0.00140*
	4	0.16075	0.16285	*-0.00210*
	5	0.16075	0.16285	*-0.00210*
3	1	0.16075	0.15885	0.00190
	2	0.16065	0.15860	0.00205
	3	0.16115	0.15900	0.00215
	4	0.16125	0.15970	0.00155
	5	0.16095	0.15860	0.00235
4	1	0.16075	0.16010	0.00065
	2	0.16080	0.16000	0.00080
	3	0.16130	0.16060	0.00070
	4	0.16140	0.16060	0.00080
	5	0.16085	0.16005	0.00080
5	1	0.16075	0.15695	0.00380
	2	0.16110	0.15920	0.00190
	3	0.16105	0.15790	0.00315
	4	0.16075	0.15920	0.00155
	5	0.16070	0.15730	0.00340
6	1	0.16075	0.15980	0.00095
	2	0.16075	0.15990	0.00085
	3	0.16100	0.16030	0.00070
	4	0.16115	0.16055	0.00060
	5	0.16085	0.16010	0.00075
7	1	0.16085	0.15980	0.00105
	2	0.16080	0.16000	0.00080
	3	0.16165	0.16075	0.00090
	4	0.16135	0.16075	0.00060
	5	0.16105	0.15000	0.01105
8	1	0.16095	0.15975	0.00120
	2	0.16145	0.16065	0.00080
	3	0.16115	0.16045	0.00070
	4	0.16085	0.16000	0.00085
	5	0.16070	0.15980	0.00090
***Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error**				

Maximum	0.01105
Average	0.00111

Piston Ring Gap Measurements, in

Cylinder	Ring No.	Before	After	Delta
1	1	0.022	0.027	0.005
	2	0.039	0.044	0.005
	3	0.022	0.026	0.004
2	1	0.022	0.024	0.002
	2	0.039	0.041	0.002
	3	0.023	0.026	0.003
3	1	0.022	0.029	0.007
	2	0.040	0.052	0.012
	3	0.022	0.029	0.007
4	1	0.021	0.025	0.004
	2	0.038	0.044	0.006
	3	0.023	0.026	0.003
5	1	0.022	0.036	0.014
	2	0.039	0.051	0.012
	3	0.024	0.034	0.010
6	1	0.021	0.025	0.004
	2	0.039	0.044	0.005
	3	0.023	0.026	0.003
7	1	0.020	0.023	0.003
	2	0.039	0.044	0.005
	3	0.023	0.026	0.003
8	1	0.022	0.025	0.003
	2	0.039	0.045	0.006
	3	0.022	0.025	0.003

Ring No. 1 max increase	0.014
Ring No. 2 max increase	0.012
Ring No. 3 max increase	0.010

Ring No. 1 avg increase	0.005
Ring No. 2 avg increase	0.007
Ring No. 3 avg increase	0.005

Piston Ring Mass, grams

Cylinder	Ring No.	Before	After	Delta
1	1	22.4805	22.2550	0.2255
	2	16.9859	16.9772	0.0087
	3	15.0175	14.9588	0.0587
2	1	22.7468	22.6751	0.0717
	2	17.2684	17.2129	0.0555
	3	14.8578	14.8258	0.0320
3	1	22.9587	22.5773	0.3814
	2	17.0045	16.8721	0.1324
	3	14.9201	14.8304	0.0897
4	1	22.9774	22.8960	0.0814
	2	17.0053	16.9700	0.0353
	3	15.2437	15.2025	0.0412
5	1	22.6533	22.0803	0.5730
	2	17.0870	16.8721	0.2149
	3	15.2614	15.1345	0.1269
6	1	22.9076	22.8115	0.0961
	2	17.0016	16.9720	0.0296
	3	15.0623	15.0284	0.0339
7	1	23.0226	22.9457	0.0769
	2	17.0422	16.9989	0.0433
	3	15.0292	14.9835	0.0457
8	1	22.9787	22.8982	0.0805
	2	17.0178	16.9806	0.0372
	3	15.0248	14.9912	0.0336

Ring No. 1 max decrease	0.5730
Ring No. 2 max decrease	0.2149
Ring No. 3 max decrease	0.1269

Ring No. 1 avg decrease	0.1983
Ring No. 2 avg decrease	0.0696
Ring No. 3 avg decrease	0.0577

Connecting Rod Bearing Weight Loss, grams

Rod Bearing	Shell	Before	After	Change
1	Top	27.8556	27.6029	0.2527
	Bottom	27.8644	27.8168	0.0476
2	Top	27.8603	27.7952	0.0651
	Bottom	27.8311	27.7984	0.0327
3	Top	27.8550	27.7585	0.0965
	Bottom	27.8429	27.8280	0.0149
4	Top	27.8561	27.7933	0.0628
	Bottom	27.8027	27.7875	0.0152
5	Top	27.7268	27.6156	0.1112
	Bottom	27.7395	27.7178	0.0217
6	Top	27.7572	27.6722	0.0850
	Bottom	27.7449	27.7235	0.0214
7	Top	27.7375	27.5974	0.1401
	Bottom	27.7424	27.6941	0.0483
8	Top	27.7386	27.6353	0.1033
	Bottom	27.7536	27.7124	0.0412

Maximum	0.2527
Average	0.0725

Main Bearing Weight Loss, grams

Main Bearing	Shell	Before	After	Change
1	Top	48.5985	48.5292	0.0693
	Bottom	52.5554	52.5058	0.0496
2	Top	48.6637	48.6078	0.0559
	Bottom	52.7369	52.5588	0.1781
3	Top	93.1926	90.8908	2.3018
	Bottom	98.3749	93.1104	5.2645
4	Top	48.5219	48.4901	0.0318
	Bottom	52.5970	52.5044	0.0926
5	Top	69.4738	69.3931	0.0807
	Bottom	73.2391	73.1138	0.1253

Maximum	5.2645
Average	0.8250

Stanadyne Injection Pump Calibration/Evaluation

Pump Type : DB2831-5485 (arctic)	**SN: 12986940**
Test condition : LO228213-65T1-W-210	

PUMP RPM	***Description***	***Spec.***	***Before***	***After***	***Change***
1000	Transfer pump psi.	60-62 psi	60	70	**10**
	Return Fuel	225-375 cc	325	240	**85**
338	Low Idle	12-16 cc	14	10	**4**
	Housing psi.	8-12 psi	11	9	**2**
	Advance	3.5 deg. min	4	5	**1**
	Cold Advance Solenoid	0-1 psi.	1	1	**0**
750	Shut-Off	4 cc max.	0.1	0.5	**0.4**
900	Fuel Delivery	66.5 - 69.5cc	68.5	65.5	**3**
1600	Fuel delivery	59.5 min.	64.5	63	**1.5**
	Advance	2.5 - 3.5 deg.	3	3	**0**
	Low Idle	11 - 12 deg.	11	10.5	**0.5**
1825	Fuel Delivery	33 cc min.	54	63	**9**
1950	High Idle	15 cc max.	5.3	13	**7.7**
	Transfer pump psi.	125 psi max.	110	115	**5**
200	Fuel Delivery	58 cc min.	59.5	61	**1.5**
	Shut-Off	4 cc max.	0.1	0.1	**0**
75	Fuel Delivery	37 cc min.	47	47	**0**
	Transfer pump psi.	16 psi min.	26	30	**4**
	Housing psi.	0 -12 psi	10	9.5	**0.5**
	Date		4/9/2007	2/16/2009	

Photographs

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Piston Skirt Thrust - Best **Cyl. 6**

Piston Skirt Anti-thrust - Best **Cyl. 6**

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Piston Skirt Thrust - Worst **Cyl. 1**

Piston Skirt Anti-thrust - Worst **Cyl. 1**

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Piston Rings - Best Cyl. 8

Piston Rings - Worst Cyl. 5

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	EOT Date:	20090202
Test No.:	LO228213-65T1-W-210	Test Length:	210

Piston Undercrown - Best Cyl. 1

Piston Undercrown - Worst Cyl. 4

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Engine Block Cylinder Bore - Best **Cyl. 8**

Engine Block Cylinder Bore - Worst **Cyl. 1**

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Exhaust and Intake Valve - Best Cyl. 1

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Exhaust and Intake Valve - Worst Cyl. 5

GEP 6.5L - Tactical Wheeled Vehicle Extended Cycle

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Rod Bearings

Oil Code:	LO-228213	**EOT Date:**	20090202
Test No.:	LO228213-65T1-W-210	**Test Length:**	210

Main Bearings

APPENDIX B

6.5L Turbocharged HMMWV

Test Number: LO241026-65T1-NATO-400

Test Procedure: NATO Standard Engine Laboratory Test

EVALUATION OF MIL-PRF-46167D OEA 0W-30 ARCTIC OIL

Work Directive No. 42

6.5L Turbocharged HMMWV

Test Lubricant: LO-241026
Experimental Arctic Oil – 0W30 OEA Lubrizol
Test Fuel: JP-8
Test Number: LO241026-65T1-NATO-400
Start of Test Date: June 21, 2009
End of Test Date: July 27, 2009
Test Duration: 400 Hours
Test Procedure: NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Introduction

This test was used to evaluate experimental arctic oil, Lubrizol OEA 0W30, for use in military tactical vehicles using the procedures outlined in the NATO Standard Engine Laboratory Test (AEP-5 Edition 3). This work was completed in support of Work Directive 42, Single Common Powertrain Lubricants for Combat/Tactical Equipment.

Test Engine

The experimental oil was evaluated in the General Engine Products (GEP) 6.5L turbocharged diesel engine, representative of engines currently fielded in High Mobility Multipurpose Wheeled Vehicles (HMMWV). Prior to testing, the engine was disassembled and measured for pre-test wear. Engine clearances and specifications were verified, and the engine was reassembled following standard assembly procedures.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for GEP engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorbing dynamometer was used to supply engine loading. Engine oil, fuel, and coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers. Engine intake air was supplied at ambient conditions, with its flowrate measured using pressure drop across a laminar flow element (LFE).

Engine Run-In

Prior to testing, the engine was run-in using the candidate oil following procedures outlined below. Cyclic modes were repeated for a total of 24 cycles. Total runtime for engine run-in was approximately 6 hours.

Time, min	Mode	Speed, RPM	Torque, lb*ft	Coolant Out, °F	Oil Galley, °F
10	Steady State	1500	10	215	220
10	Steady State	1600	109	215	220
10	Steady State	2400	145	215	220
10	Steady State	3200	165	215	220
1	Cyclic	900	0	215	220
2	Cyclic	2600	50%	215	220
2	Cyclic	1800	1%	215	220
2	Cyclic	1200	25%	215	220
2	Cyclic	1800	50%	215	220
2	Cyclic	3200	5%	215	220
2	Cyclic	2200	50%	215	220

Figure 1 - Test Engine Run-In Procedure

Pre-Test Engine Performance Check

After completion of engine run-in, a full load powercurve was completed from 1000 rpm to rated engine speed (3400 rpm) to determine pre-test engine performance. The pre-test engine performance check was completed using the same oil charge used during the engine run-in segment. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during oil evaluation was the standard 400 hr NATO cycle as outlined in AEP-5 Edition 3. The test cycle consists of 10 modes running for a total of 10 hours. This cycle is then repeated 40 times. Total daily run-time was 20 hrs, or 2 cycles, with a 4 hr soak overnight before resuming the next day testing. This was done to shorten the total number of days the test would be running. Engine oil, coolant, and fuel temperatures were elevated to simulate conditions consistent with desert warfare use. Engine operating parameters were controlled throughout testing as specified in the table below.

Mode #	Speed [RPM]	Load [%]	Duration [hours]	Oil Temp [F]	Coolant Temp [F]	Fuel Temp [F]
1	Idle	0	0.5	260	205	100
2	3400	100	2	260	205	100
3	Governed	0	0.5	260	205	100
4	2550	100	1	260	205	100
5	Idle to 3400 - Cyclic	0 to 100 - Cyclic	2	260	205	100
6	2040	100	0.5	260	205	100
7	Idle	0	0.5	260	205	100
8	3520	70	0.5	260	205	100
9	1800	100	2	260	205	100
10	2040	50	0.5	260	205	100

Figure 2 - Test Cycle Operating Parameters

Engine coolant was a 60/40 blend of ethylene glycol antifreeze and deionized water. Test fuel was JP-8.

Oil Sampling

Eight ounces of engine oil was sampled every 20 hrs for used oil analysis. Engine oil analysis consisted of the following tests. All oil samples were weighed and logged to take into account during calculations of total engine oil consumption for the test duration.

Every 20 Hours		
ASTM	**D4739**	Total Base Number
ASTM	**D664**	Total Acid Number
ASTM	**D445**	Kinematic Viscosity @ 100° C
ASTM	**API Gravity**	API Gravity
ASTM	**D4052**	Density
ASTM	**TGA Soot**	TGA Soot
ASTM	**E168**	Oxidation
ASTM	**E168**	Nitration
ASTM	**D5185**	Wear Metals by ICP

Figure 3 - Used Oil Analysis Procedures

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily and replenished as needed to restore oil level to the full mark. This process occurred daily after the completion of the 4 hr soak prior to restarting testing the next day. All oil additions were weighed and logged to take into account during calculation of total engine oil consumption for the test duration.

Oil Change Intervals

After every 100 hours of testing the oil was changed as dictated by the NATO cycle instructions. The used oil and filter were weighed, as removed, and the new oil weighed, as added, to track oil consumption.

Post-Test Engine Performance Check

After completion of each 100 hours of testing, and before the oil change, a full load powercurve was completed from 1000 rpm to rated engine speed (3400 rpm) to determine engine performance. Powercurve plots can be seen in the Engine Performance Curves section.

Engine Operating Conditions Summary

Below is a summary of the engine operating conditions over the duration of the 400 engine hours. Please note that, for consistency, the data excludes the 15 second ramps into the summarized modes.

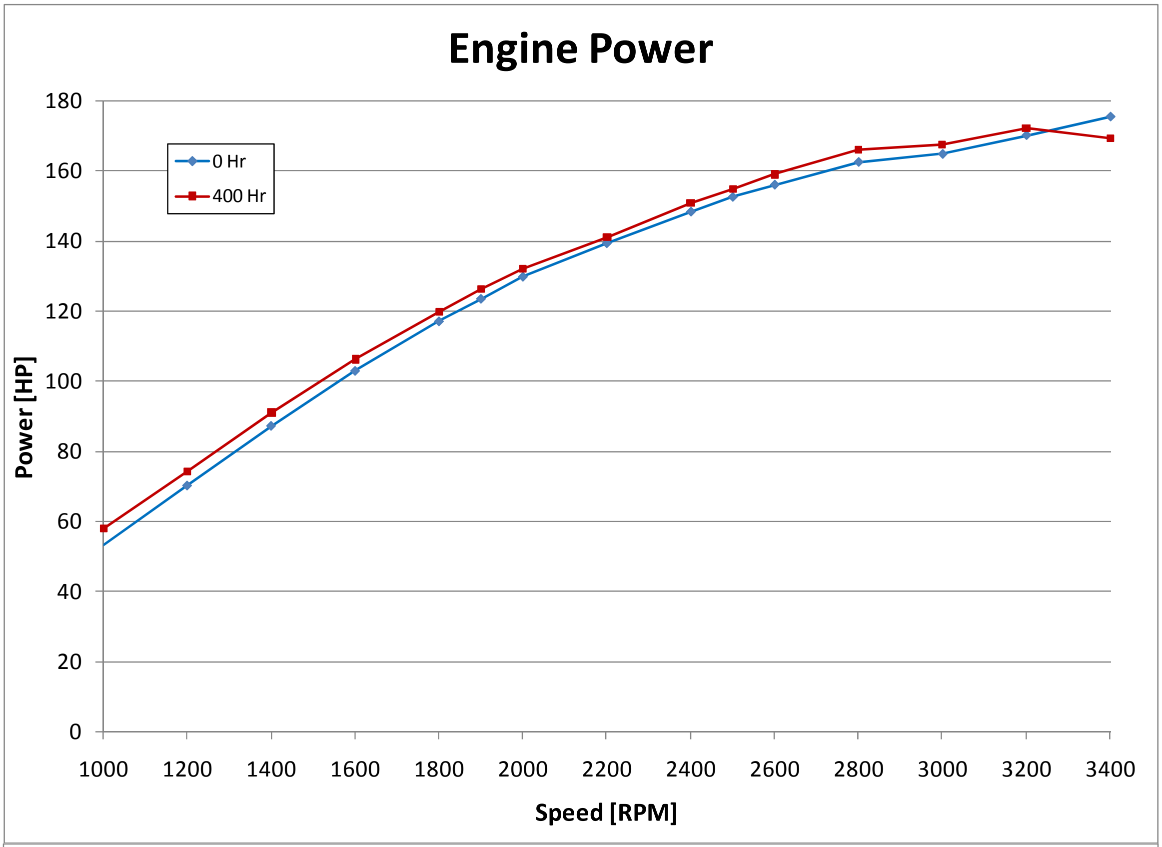
Performance	0 to 100 Hours, Nato Mode 2 Mean	Std. Dev.	Min	Max	100 to 200 Hours, Nato Mode 2 Mean	Std. Dev.	Min	Max
Engine Speed [rpm]	3400.0	1.0	3395	3405	3400.0	0.4	3398	3401
Power [hp]	181.3	1.1	177.6	187.2	172.8	2.3	168.6	183.7
Torque [ft-lb]	280.1	1.8	274	289	266.9	3.5	260	284
Fuel Consumption [lb/hr]	82.4	0.2	81.36	83.76	79.8	1.0	77.76	84.11
BSFC [lb/hp-hr]	0.454	0.003	0.441	0.464	0.462	0.003	0.454	0.47
Temperatures [F]								
Oil Sump	260.0	0.9	241.4	262.8	260.5	2.6	232.1	264.2
Water Jacket Inlet	194.1	0.4	192.4	195.7	194.4	0.6	192.7	198.2
Water Jacket Outlet	205.0	0.3	203.5	206.3	205.0	0.5	203.6	206.9
Fuel Inlet to Pump	99.3	1.0	92.4	102.8	99.3	1.7	91.8	102.9
Inlet Air	118.7	4.8	90.3	124.9	95.4	4.6	85.9	113
Intake Manifold Air	181.1	2.5	158.4	187.5	174.9	4.3	158.2	188.7
Exhaust Port Cylinder 1	1258.0	12.1	1168.4	1276.7	1196.5	25.2	1109.4	1292.6
Exhaust Port Cylinder 2	1231.3	13.5	1136.1	1247	1204.4	16.5	1117.9	1260.7
Exhaust Port Cylinder 3	1307.0	12.4	1209	1322.8	1289.1	16.6	1204.7	1349.5
Exhaust Port Cylinder 4	1268.6	13.8	1165.8	1286.6	1231.0	21.4	1140.7	1308.2
Exhaust Port Cylinder 5	1299.2	13.5	1192.8	1313.7	1266.5	18.7	1175.3	1335.6
Exhaust Port Cylinder 6	1259.2	12.1	1171.9	1274.3	1211.7	20.4	1111.9	1291.1
Exhaust Port Cylinder 7	1282.3	15.5	1179.1	1354.9	1237.6	24.0	1140.8	1326.4
Exhaust Port Cylinder 8	1251.8	13.6	1151.1	1271.5	1239.6	17.2	1147.6	1295.5
Exhaust, Before Turbo	1317.4	12.9	1207.4	1333.8	1277.1	21.5	1175.9	1358.2
Exhaust, After Turbo	1174.6	14.6	1001.2	1188.8	1137.9	23.1	972.4	1209.9
Pressures								
Oil [psiG]	39.3	0.2	38	41.5	38.6	0.4	37.9	42.5
Barometer [psiA]	14.3	0.0	14.29	14.35	14.3	0.0	14.26	14.33
Intake, Before Compressor [psiA]	13.9	0.0	13.88	13.96	13.9	0.0	13.87	13.94
Intake, After Compressor [psiA]	18.4	0.1	18.2	18.8	18.4	0.1	18.1	18.6
Exhaust, After Turbo [psiG]	0.59	0.11	-0.02	0.68	0.52	0.03	0.33	0.59
Other								
Mass Air Flow [lb/hr]	1521.4	21.3	1495.8	1640.0	1617.3	16.1	1545.1	1659.7
Air-Fuel Ratio	18.5	0.3	18	19.8	20.3	0.4	18.7	21.2
Dry Bulb Temp, In Cell [F]	101.8	3.6	83.2	111.7	97.5	4.6	87.2	107.9
Relative Humidity, In Cell [%]	27.3	3.0	19.5	46.7	33.6	6.9	21.5	50.9

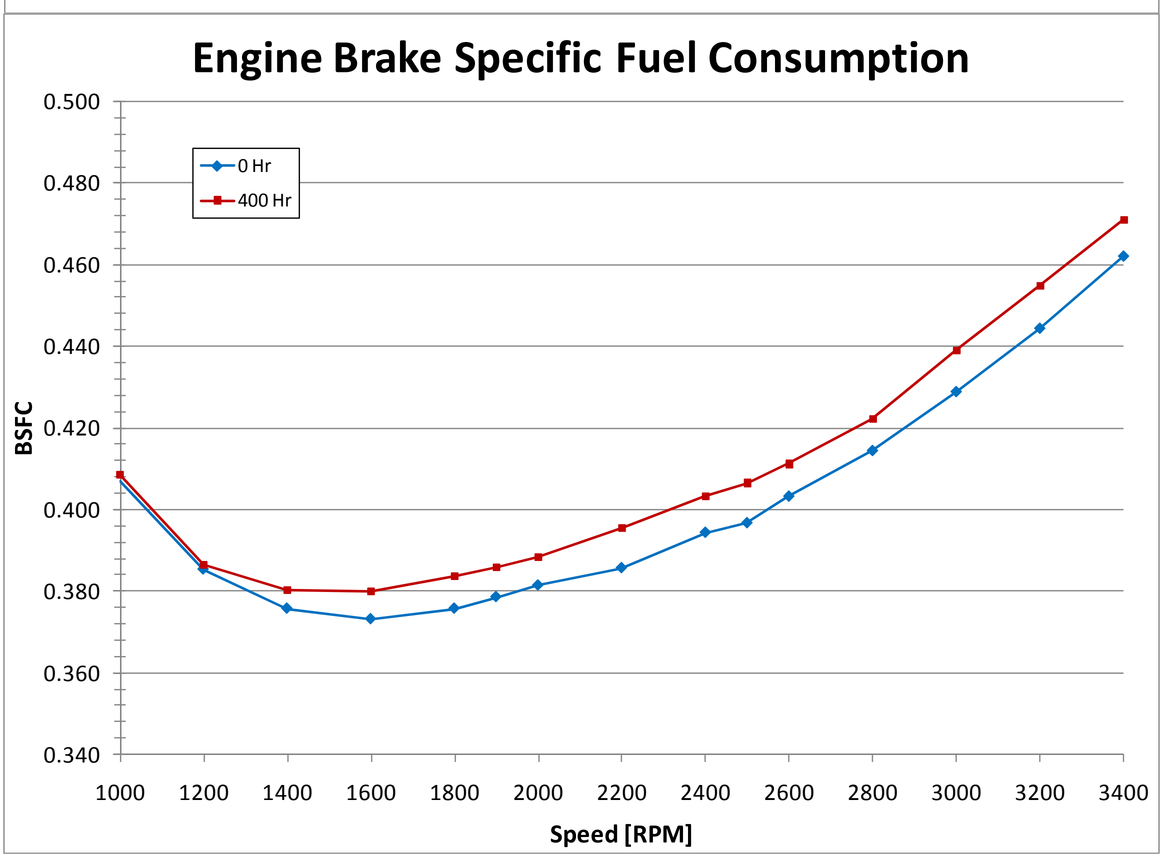
	200 to 300 Hours, Nato Mode 2					300 to 400 Hours, Nato Mode 2			
Performance	**Mean**	**Std. Dev.**	**Min**	**Max**		**Mean**	**Std. Dev.**	**Min**	**Max**
Engine Speed [rpm]	3400.0	0.4	3399	3401		3400.0	0.4	3399	3401
Power [hp]	170.4	2.0	165.3	173.6		168.2	0.6	164	170.3
Torque [ft-lb]	263.3	3.2	255	268		259.8	1.0	253	263
Fuel Consumption [lb/hr]	79.1	1.0	76.07	80.83		78.6	0.4	76.27	80.14
BSFC [lb/hp-hr]	0.464	0.002	0.457	0.471		0.467	0.002	0.46	0.475
Temperatures [F]									
Oil Sump	261.9	3.5	222.3	264.3		262.5	3.8	224.9	265.1
Water Jacket Inlet	194.5	0.6	192.4	197.1		194.5	3.8	185.5	203.3
Water Jacket Outlet	205.0	0.5	203.2	206.6		205.0	1.6	201.2	208.9
Fuel Inlet to Pump	99.5	1.8	92.2	103		99.0	1.8	89.9	101.3
Inlet Air	96.9	4.8	88.3	106.3		93.2	3.4	84.4	100.2
Intake Manifold Air	175.0	5.5	156.8	185.2		173.8	3.6	156.2	181.8
Exhaust Port Cylinder 1	1173.1	17.9	1093.4	1213.5		1160.4	11.8	1087.8	1180.6
Exhaust Port Cylinder 2	1201.3	14.5	1113.6	1226.5		1193.4	11.6	1111.2	1212.7
Exhaust Port Cylinder 3	1276.2	14.9	1185.4	1307.6		1263.3	11.5	1182.4	1281.9
Exhaust Port Cylinder 4	1234.2	17.7	1150.2	1270.5		1232.1	13.4	1150.5	1258.6
Exhaust Port Cylinder 5	1252.3	14.8	1164.7	1286		1239.2	29.7	1157.6	1591.9
Exhaust Port Cylinder 6	1211.2	17.6	1114.2	1244.6		1201.6	13.9	1110.1	1221.9
Exhaust Port Cylinder 7	1222.2	16.0	1128.9	1260.1		1214.7	11.9	1129.1	1231.4
Exhaust Port Cylinder 8	1238.2	18.0	1139	1270.6		1226.4	13.8	1129.3	1247.4
Exhaust, Before Turbo	1263.5	17.1	1161.7	1301.1		1251.0	12.3	1159.5	1267.7
Exhaust, After Turbo	1129.8	21.5	960.4	1161.9		1119.7	18.6	963.5	1138.4
Pressures									
Oil [psiG]	38.1	0.6	37	43.7		37.2	0.6	36.6	43.6
Barometer [psiA]	14.4	0.0	14.32	14.41		14.3	0.0	14.3	14.38
Intake, Before Compressor [psiA]	14.0	0.0	13.93	14.02		14.0	0.0	13.9	13.99
Intake, After Compressor [psiA]	18.5	0.1	18.1	18.7		18.5	0.1	18.1	18.8
Exhaust, After Turbo [psiG]	0.56	0.03	0.36	0.6		0.57	0.02	0.37	0.6
Other									
Mass Air Flow [lb/hr]	1609.9	11.7	1583.3	1647.3		1627.3	14.1	1603.4	1656.7
Air-Fuel Ratio	20.4	0.2	19.8	21.3		20.7	0.2	20.3	21.6
Dry Bulb Temp, In Cell [F]	97.9	4.6	87.8	107.3		96.2	4.4	85.7	105
Relative Humidity, In Cell [%]	30.6	7.4	17.2	47.7		35.1	6.9	24.4	54

	0 to 100 Hours, Nato Mode 9					100 to 200 Hours, Nato Mode 9			
Performance	**Mean**	**Std. Dev.**	**Min**	**Max**		**Mean**	**Std. Dev.**	**Min**	**Max**
Engine Speed [rpm]	1800.0	1.0	1796	1804		1800.0	0.5	1798	1802
Power [hp]	119.2	0.7	116.1	122.4		120.2	0.9	117.2	122.7
Torque [ft-lb]	347.9	2.1	339	357		350.9	2.6	342	358
Fuel Consumption [lb/hr]	44.2	0.4	43.82	55.51		45.5	0.3	44.59	46.18
BSFC [lb/hp-hr]	0.371	0.003	0.362	0.459		0.379	0.003	0.371	0.387
Temperatures [F]									
Oil Sump	260.0	1.1	257	262.4		260.0	0.8	252.8	262.2
Water Jacket Inlet	193.0	1.3	189	195.7		192.9	1.3	189.4	195.5
Water Jacket Outlet	205.1	1.1	202.6	207.8		205.0	1.1	202.7	207.2
Fuel Inlet to Pump	99.7	1.2	95.1	103		99.0	1.5	95	103.1
Inlet Air	103.3	4.9	89.6	121.3		93.4	5.9	84	104.5
Intake Manifold Air	201.6	4.2	196.3	215.4		204.2	6.4	191.1	216.9
Exhaust Port Cylinder 1	922.1	14.7	907.2	978.4		949.3	11.3	924.8	978.6
Exhaust Port Cylinder 2	837.5	16.6	823.8	905.1		879.8	10.9	857.1	908.2
Exhaust Port Cylinder 3	914.0	16.5	899.3	978.6		975.6	68.6	928.3	1314.5
Exhaust Port Cylinder 4	905.1	21.6	887.5	977.9		967.0	11.7	938.4	994.2
Exhaust Port Cylinder 5	941.6	13.7	926.5	1003.5		964.0	12.5	937.6	1007.9
Exhaust Port Cylinder 6	912.3	16.2	897.5	975.6		965.9	11.7	940.9	992.4
Exhaust Port Cylinder 7	937.2	58.6	914.4	1645.2		964.8	11.5	938.4	1008.9
Exhaust Port Cylinder 8	906.8	17.7	891	976.3		961.7	11.4	934.9	986.9
Exhaust, Before Turbo	976.2	15.4	961.2	1041.1		1005.8	12.1	978.9	1041.9
Exhaust, After Turbo	816.2	16.6	804	911.8		853.2	10.3	828.4	919.8
Pressures									
Oil [psiG]	22.4	0.5	21.5	24.2		22.8	0.3	22.2	24.5
Barometer [psiA]	14.3	0.0	14.26	14.34		14.3	0.0	14.26	14.33
Intake, Before Compressor [psiA]	14.1	0.0	14.05	14.17		14.1	0.0	14.06	14.13
Intake, After Compressor [psiA]	22.9	0.2	22.2	23.2		22.8	0.1	22.4	23
Exhaust, After Turbo [psiG]	-0.02	0.03	-0.13	0.08		0.01	0.02	-0.02	0.05
Other									
Mass Air Flow [lb/hr]	1005.4	16.9	948.4	1041.8		1041.1	17.0	1011.2	1071.9
Air-Fuel Ratio	22.8	0.5	18.3	23.2		22.9	0.4	22.2	23.5
Dry Bulb Temp, In Cell [F]	92.9	4.7	89.3	109.8		96.4	5.4	87.9	106.2
Relative Humidity, In Cell [%]	34.4	6.6	14	40.2		34.7	9.5	19	50.4

	200 to 300 Hours, Nato Mode 9					300 to 400 Hours, Nato Mode 9			
Performance	**Mean**	**Std. Dev.**	**Min**	**Max**		**Mean**	**Std. Dev.**	**Min**	**Max**
Engine Speed [rpm]	1800.0	0.5	1798	1802		1800.0	0.9	1796	1804
Power [hp]	119.9	1.2	116.7	122.7		119.7	0.7	116.5	121
Torque [ft-lb]	349.8	3.5	340	358		349.4	1.9	340	353
Fuel Consumption [lb/hr]	45.4	0.4	44.58	46.26		45.3	0.1	44.53	45.54
BSFC [lb/hp-hr]	0.379	0.002	0.371	0.386		0.378	0.001	0.375	0.387
Temperatures [F]									
Oil Sump	259.7	1.2	251.8	261.1		259.2	1.1	251.7	260.7
Water Jacket Inlet	193.0	1.3	189.7	195.9		193.1	1.5	189.6	196.1
Water Jacket Outlet	205.0	1.1	202.6	207.4		205.0	1.3	202	207.5
Fuel Inlet to Pump	99.2	1.3	96	101.9		98.5	0.8	95.5	101.7
Inlet Air	96.6	6.0	87	107.2		89.2	3.8	85.3	101.3
Intake Manifold Air	208.1	6.1	197.5	217.2		202.1	3.9	194.9	214.9
Exhaust Port Cylinder 1	934.0	7.1	914.4	952.2		921.6	5.4	908.7	945.1
Exhaust Port Cylinder 2	878.3	7.9	858.9	907.7		871.1	4.9	865	894.9
Exhaust Port Cylinder 3	943.6	7.3	923.5	962.3		935.7	3.8	919	951.5
Exhaust Port Cylinder 4	966.5	7.5	949.2	984.5		957.6	6.7	949.7	981.8
Exhaust Port Cylinder 5	956.0	7.6	940	975.3		943.1	3.8	929.3	957.8
Exhaust Port Cylinder 6	965.0	7.8	947.5	985.9		954.1	5.0	946.7	975
Exhaust Port Cylinder 7	956.8	7.3	939.1	979.3		948.0	3.7	933.6	964.4
Exhaust Port Cylinder 8	962.5	8.7	946.3	984.9		955.2	4.1	942.3	975.9
Exhaust, Before Turbo	997.5	7.9	980.2	1016.5		986.6	4.1	973.9	1003.8
Exhaust, After Turbo	845.3	7.7	832.4	891		836.6	4.4	830.7	865.2
Pressures									
Oil [psiG]	22.4	0.4	21.6	24.5		22.1	0.4	21.6	24.3
Barometer [psiA]	14.4	0.0	14.32	14.41		14.3	0.0	14.27	14.38
Intake, Before Compressor [psiA]	14.2	0.0	14.11	14.2		14.1	0.0	14.06	14.18
Intake, After Compressor [psiA]	23.0	0.2	22.8	23.3		23.1	0.1	22.7	23.2
Exhaust, After Turbo [psiG]	0.02	0.02	0	0.06		0.04	0.02	0	0.06
Other									
Mass Air Flow [lb/hr]	1042.2	18.1	1014.2	1072.1		1066.5	14.8	1020.2	1083.0
Air-Fuel Ratio	23.0	0.3	22.4	23.7		23.6	0.3	22.6	24.1
Dry Bulb Temp, In Cell [F]	98.3	5.6	89.8	107.2		92.6	3.8	89.1	104.2
Relative Humidity, In Cell [%]	29.6	10.1	14.4	46.3		41.9	8.8	15	51.4

Engine Performance Curves

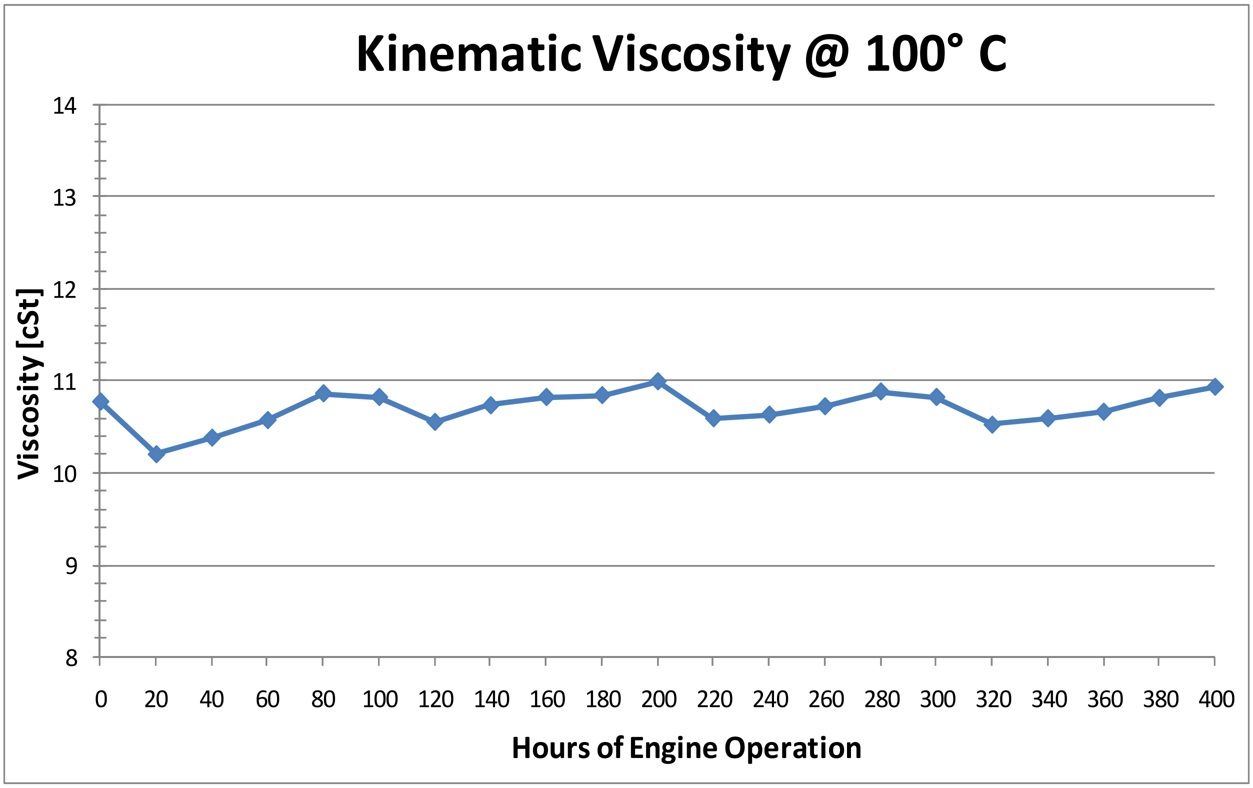


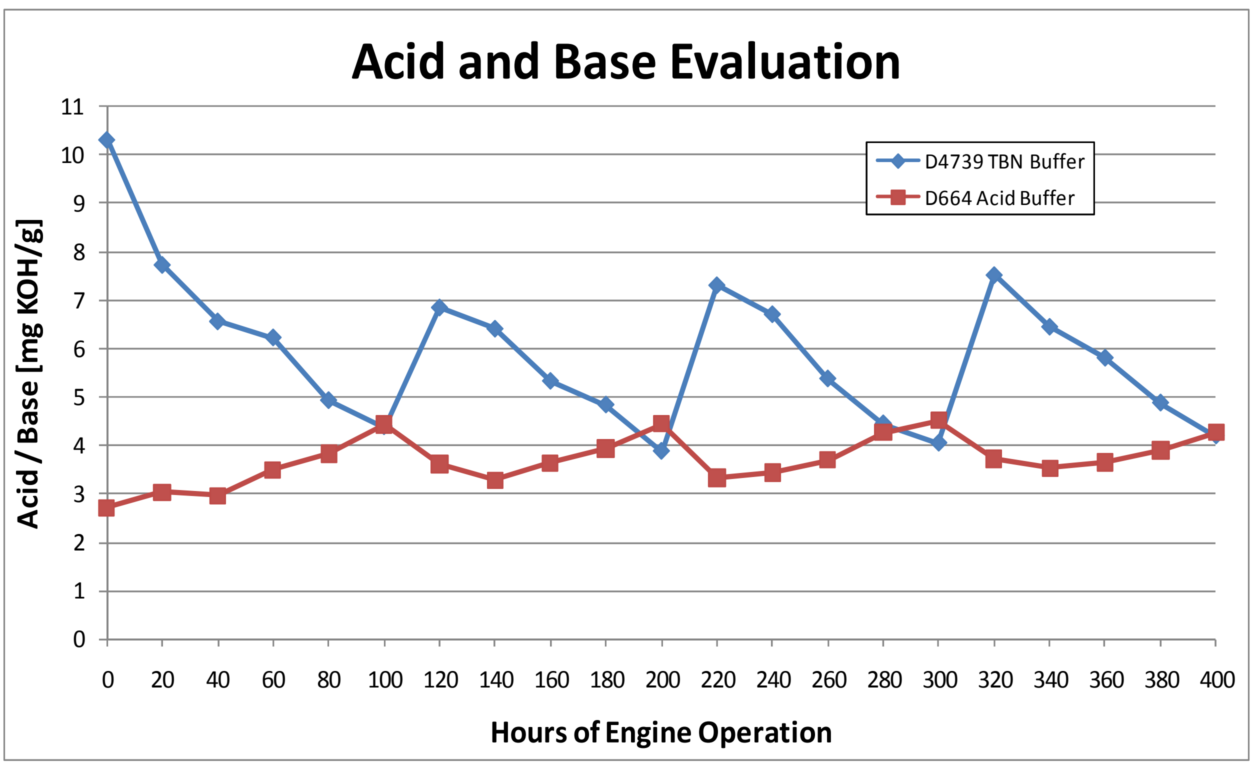


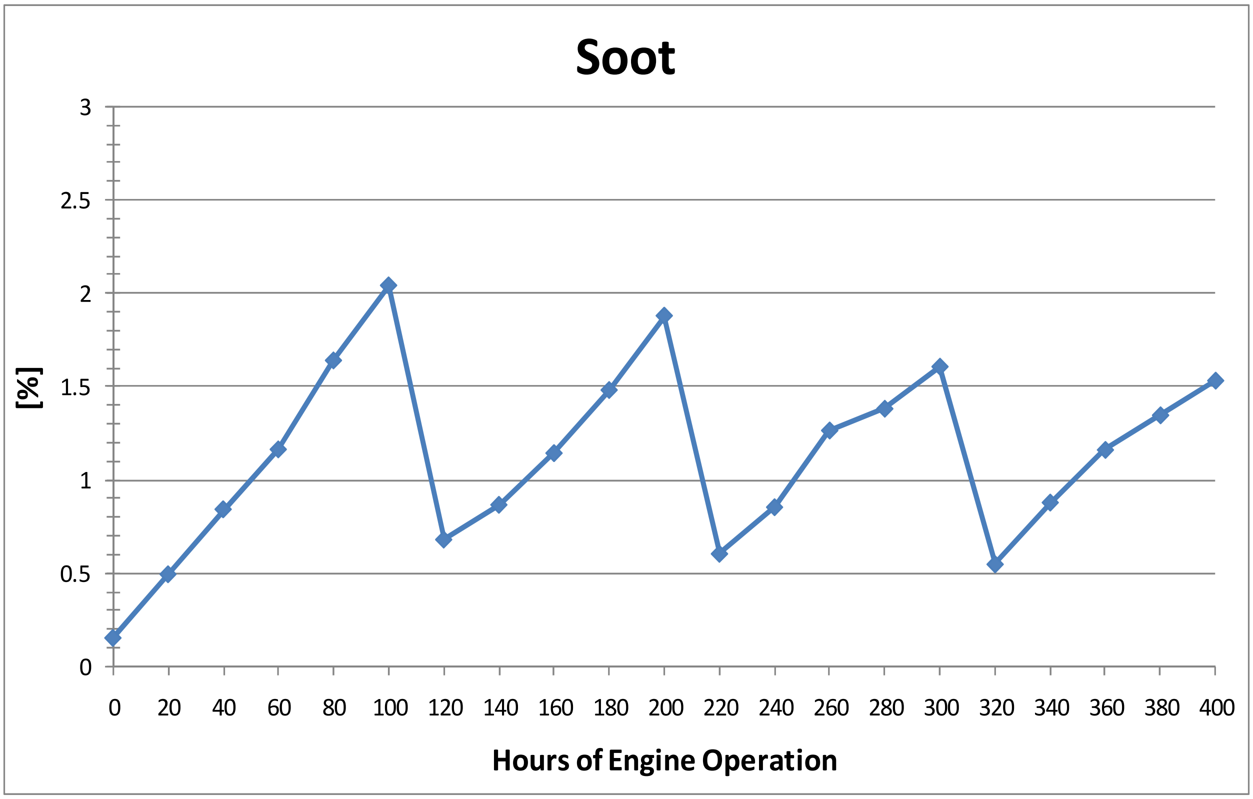
Engine Oil Analysis

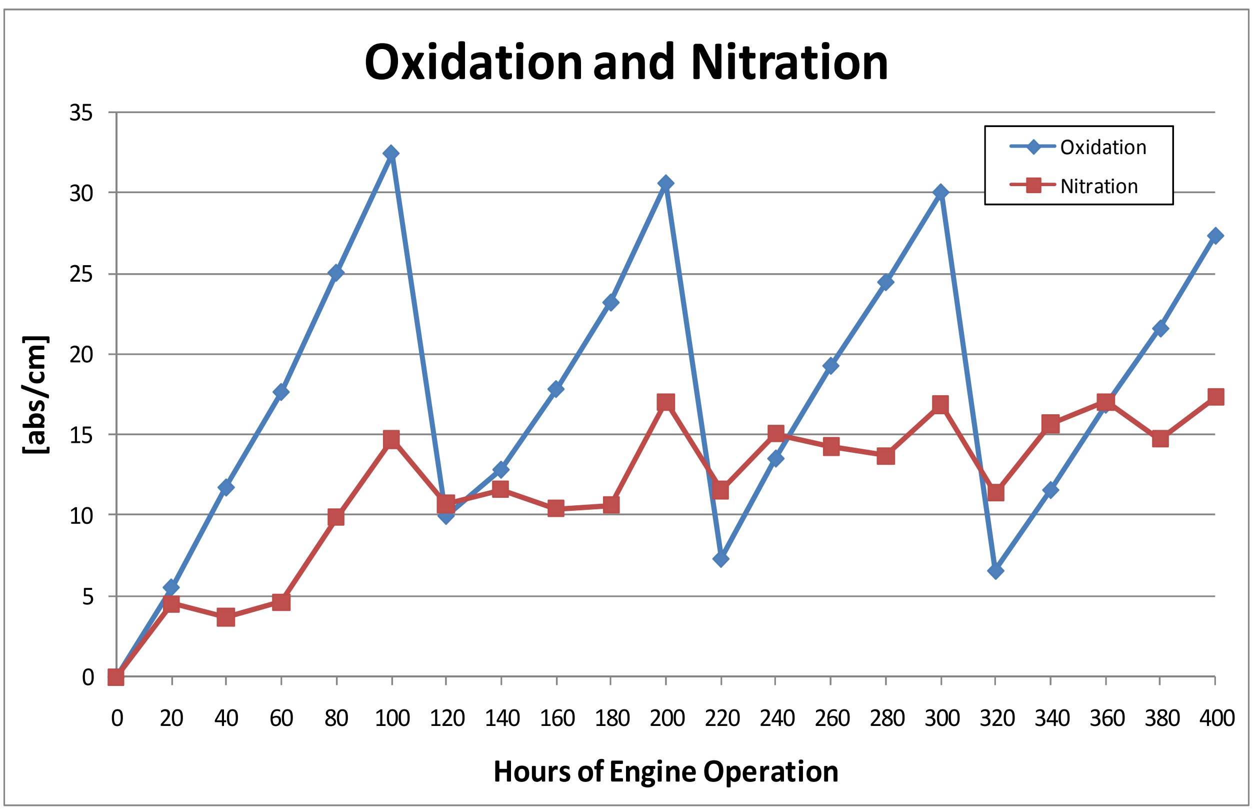
Property	ASTM Test No.	Test Hours																				
		0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
Total Base Number [mg KOH/g]	D4739	10.32	7.73	6.56	6.23	4.93	4.39	6.85	6.41	5.53	4.84	3.88	7.31	6.71	5.38	4.45	4.05	7.52	6.45	5.81	4.88	4.20
Total Acid Number [mg KOH/g]	D664	2.71	3.03	2.95	3.49	3.82	4.43	3.61	3.28	3.63	3.93	4.44	3.33	3.43	3.69	4.26	4.51	3.72	3.51	3.65	3.89	4.27
Viscosity @ 100° C [cSt]	D445	10.78	10.21	10.39	10.58	10.87	10.83	10.56	10.74	10.83	10.85	11.00	10.60	10.64	10.73	10.89	10.83	10.53	10.60	10.67	10.82	10.94
Density [g/mL]	D4052	0.8493	0.8534	0.8569	0.8606	0.8615	0.8696	0.8563	0.8578	0.8607	0.8640	0.8680	0.8545	0.8581	0.8612	0.8640	0.8699	0.8540	0.8571	0.8601	0.8628	0.8660
Soot (TGA)	Soot	0.157	0.497	0.844	1.164	1.639	2.040	0.682	0.868	1.144	1.481	1.878	0.606	0.855	1.265	1.381	1.606	0.550	0.880	1.161	1.346	1.531
Oxidation [Abs/cm]	E168 FTNG	0.00	5.54	11.73	17.64	25.02	32.41	9.97	12.83	17.82	23.18	30.56	7.31	13.52	19.26	24.44	30.00	6.57	11.57	16.85	21.57	27.31
Nitration [Abs/cm]		0.00	4.52	3.69	4.62	9.88	14.68	10.71	11.63	10.43	10.62	17.04	11.57	15.09	14.26	13.70	16.85	11.39	15.65	17.04	14.72	17.31
Wear Metals by ICP [ppm]	D5185																					
Al		1	4	8	8	9	9	2	2	3	3	4	2	2	2	3	3	2	2	2	2	2
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		<1	2	2	5	5	5	1	2	2	2	3	5	4	<1	1	1	1	<1	1	<1	<1
Ca		3519	3763	3917	4053	4166	4412	3877	3857	4060	4130	4339	3789	3906	4136	4234	4457	3813	3909	3983	4127	4347
Cr		<1	3	8	9	11	11	2	2	4	4	5	1	2	3	3	4	1	2	2	3	3
Cu		<1	16	22	29	36	36	7	7	10	18	21	4	5	7	9	11	2	3	4	6	7
Fe		2	79	183	249	361	478	118	140	215	285	373	69	113	161	209	265	56	87	121	164	216
Pb		<1	27	35	40	53	73	12	12	17	23	41	8	14	19	28	42	8	11	13	17	28
Mg		10	11	13	14	15	17	12	12	13	13	14	11	12	13	13	14	11	12	12	11	13
Mn		<1	1	3	4	4	5	1	1	2	2	3	<1	1	1	2	2	<1	<1	1	1	2
Mo		<1	11	25	30	34	34	7	7	9	9	11	3	4	6	6	8	2	3	4	5	5
Ni		<1	3	7	8	9	10	2	2	3	3	4	<1	1	2	2	3	<1	1	1	2	2
P		1302	1201	1182	1209	1241	1278	1224	1227	1230	1286	1316	1244	1212	1246	1256	1311	1227	1226	1188	1254	1284
Si		3	15	18	20	21	21	8	8	10	10	11	6	7	8	7	8	5	6	7	6	8
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	5	<5	6	5	5	5	<5	<5	5	<5	<5	<5	5	5	<5	<5	<5	5	<5	5
Sn		<1	9	14	15	17	19	4	4	5	5	6	2	3	4	4	6	2	2	3	3	4
Zn		1514	1514	1557	1622	1683	1728	1545	1574	1622	1680	1735	1517	1551	1613	1668	1725	1520	1525	1606	1628	1686
K		8	6	<5	5	<5	5	5	<5	8	<5	5	6	<5	5	<5	<5	<5	<5	5	<5	<5
Sr		1	<1	1	<1	1	<1	<1	<1	<1	1	1	1	1	<1	2	1	1	2	<1	2	2
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

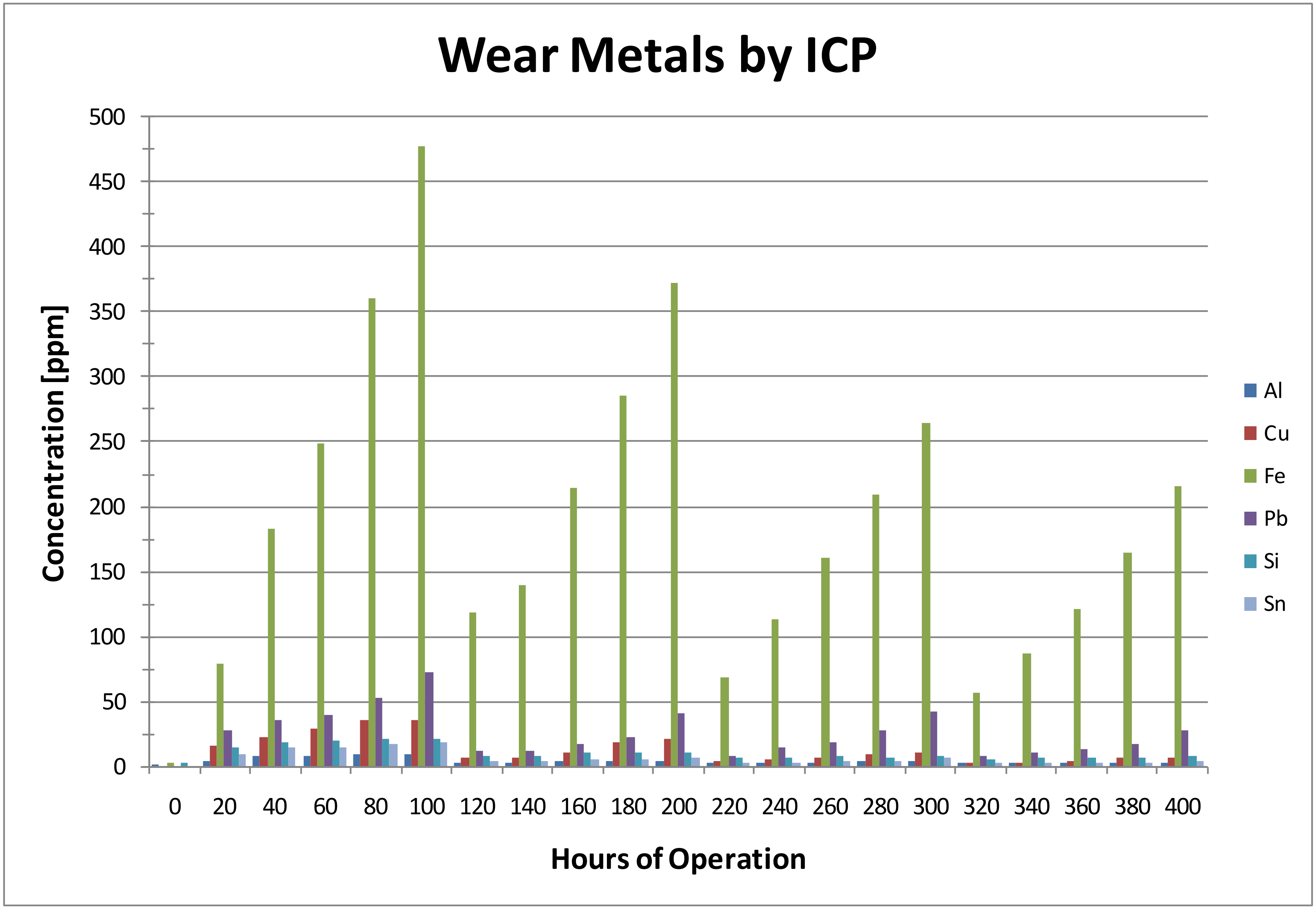
Engine Oil Analysis Trends






Soot
[%]
3
2.5
2
1.5
1
0.5
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Hours of Engine Operation


Oxidation and Nitration
Oxidation
Nitration
[abs/cm]
35
30
25
20
15
10
5
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Hours of Engine Operation


Wear Metals by ICP
Concentration [ppm]
500
450
400
350
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
Hours of Operation
Al
Cu
Fe
Pb
Si
Sn

Oil Consumption Data

Average oil consumption per test hour was 0.061 lbs/hr.

Hours	Additions (lbs)	Samples (lbs)	Consumption (lbs)	Consumption Accumulated
20	2.20	0.43	*1.77*	*1.77*
40	2.23	0.44	*1.79*	*3.56*
60	2.30	0.47	*1.83*	*5.39*
80	1.71	0.45	*1.26*	*6.65*
100	1.31	0.46	*0.85*	*7.50*
120	2.37	0.48	*1.89*	*9.39*
140	1.61	0.42	*1.19*	*10.58*
160	1.26	0.47	*0.79*	*11.37*
180	1.29	0.49	*0.80*	*12.17*
200	1.63	0.47	*1.16*	*13.33*
220	1.27	0.47	*0.80*	*14.13*
240	1.57	0.46	*1.11*	*15.24*
260	1.56	0.47	*1.09*	*16.33*
280	1.42	0.48	*0.94*	*17.27*
300	1.47	0.48	*0.99*	*18.26*
320	1.74	0.49	*1.25*	*19.51*
340	1.31	0.47	*0.84*	*20.35*
360	1.42	0.47	*0.95*	*21.30*
380	1.25	0.49	*0.76*	*22.06*
400	1.19	0.48	*0.71*	*22.77*
	Total Fills	55.34	**Total Additions**	32.11
	Total Drains	53.55	**Total Samples**	9.34
		(Total Fills + Additions)	87.45	
		- (Total Drains + Samples)	62.89	
		= Total Oil Consumption	**24.56**	

List of Engine Shutdowns and Corrective Actions

The engine itself did not have any mechanical failures, but there were several issues related to the test stand and other equipment. After each shutdown, the engine was resumed at the start of the mode where the failure occurred, according to the NATO test procedure.

Test Time	Shutdown Failure	Corrective Action
9.5 hours	Engine overspeed	Modified controller for step 10
72 hours	Loose bolt on load cell	Replaced load cell bolt
76 hours	Exhaust flex pipe disconnected	Replaced exhaust flex pipe
90 hours	EGT #7 erratic	Replaced thermocouple
106 hours	Cooling tower	Cooling tower repaired
137 hours	Cooling tower	Cooling tower repaired
167 hours	EGT #3 erratic	Replaced thermocouple
310 hours	Engine overspeed	Modified controller for step 10
331 hours	No fuel	Fuel line routed back to correct tank

Post Test Engine Ratings

Ratings	Clyinder Number								
	1	2	3	4	5	6	7	8	Avg
Ring Sticking									
Ring No.1	No	No	No	No	No	No	No	No	--
Ring No.2	No	No	No	No	No	No	No	No	--
Ring No.3	No	No	No	No	No	No	No	No	--
Scuffing % Area									
Ring No.1	0	0	0	0	0	0	0	0	0.00
Ring No.2	0	0	0	0	0	0	0	0	0.00
Ring No.3	0	0	0	0	0	0	0	0	0.00
Piston Crown	0	0	0	0	0	0	0	0	0.00
Piston Skirt	0	0	0	0	0	0	0	0	0.00
Cylinder Liner, %	0	0	0	0	0	0	0	0	0.00
Piston Carbon, Demerits									
No.1 Groove	96.00	90.00	94.00	66.25	97.00	100.00	99.50	92.50	91.91
No.2 Groove	32.75	2.50	22.25	16.75	5.25	6.25	8.25	13.00	13.38
No.3 Groove	--	--	--	--	--	--	--	--	--
No.1 Land	54.50	69.00	70.00	45.00	67.00	63.00	69.50	56.00	61.75
No.2 Land	33.25	6.00	26.50	27.50	17.00	11.00	17.75	24.75	20.47
No.3 Land	3.00	--	0.50	3.50	--	2.00	--	6.25	3.05
Upper Skirt	--	--	--	--	--	--	--	--	--
Under Crown	--	--	--	--	--	--	--	--	--
Front Pin Bore	--	--	--	--	--	--	--	--	--
Rear Pin Bore	--	--	--	--	--	--	--	--	--
Piston Lacquer, Demerits									
No.1 Groove	--	--	--	--	--	--	--	--	--
No.2 Groove	0.80	2.66	2.16	1.24	2.57	1.77	2.21	1.66	1.88
No.3 Groove	1.78	2.38	1.58	1.62	2.30	1.72	1.88	1.70	1.87
No.1 Land	0.30	--	--	0.04	--	0.02	0.90	0.02	0.26
No.2 Land	0.82	3.08	0.67	0.74	1.06	1.88	2.09	0.82	1.40
No.3 Land	1.65	2.20	2.16	1.05	1.88	2.28	2.14	1.76	1.89
Upper Skirt	0.96	0.96	0.83	0.72	1.10	0.65	0.77	1.04	0.88
Under Crown	2.38	1.87	4.20	3.00	2.78	2.77	3.75	2.52	2.91
Front Pin Bore	1.97	4.20	2.40	2.00	2.08	1.62	1.62	2.00	2.24
Rear Pin Bore	2.64	3.35	2.40	2.00	1.94	1.77	2.00	2.37	2.31
Total, Demerits	232.80	188.20	229.65	171.41	201.96	196.73	212.36	206.39	204.94
Miscellanous									
Top Groove Fill, %	97	90	91	78	97	100	100	94	93.38
Intermediate Groove Fill, %	27	1	18	5	2	2	4	5	8.00
Top Land Heavy Carbon, %	42	59	60	29	56	52	63	42	50.38
Top Lan Flaked Carbon, %	0	0	0	0	0	0	0	0	0.00
Valve Tulip Deposits, Merits									
Exahust	9.0	9.0	9.0	8.9	9.0	9.0	9.0	9.0	8.99
Intake	6.4	7.0	7.0	6.3	6.7	7.0	7.1	6.7	6.78

Engine Measurement Changes

Engine Rebuild Measurements, inches

Cylinder Bore	Minimum	Maximum	Average	Spec:
Inside Diameter	4.0541	4.0555	4.0547	Cylinder 1 thru 6 ID 4.054"-4.075"
Out of Round	0.0000	0.0008	0.0003	Cylinder 7 thru 8 ID 4.055"-Maximum 0.008"
Taper	0.0001	0.0007	0.0003	
Piston Skirt Diameter	4.0500	4.0510	4.0509	
Piston Skirt to Cylinder Bore Clearance	0.0031	0.0045	0.0038	Cylinder 1 thru 7 0.003"-0.004" Cylinder 7 thru 8 0.004"-0.005"
Piston Ring End Gaps				
Top Ring	0.020	0.022	0.021	
Second Ring	0.041	0.042	0.042	
Oil Control Ring	0.020	0.023	0.021	
Ring To Groove Clearance				
Second Ring	0.0016	0.0016	0.0016	0.0015"-0.003"
Oil Control Ring	0.0016	0.0018	0.001675	0.0015"-0.0035"
Piston Pin				
Piston Pin Diameter	1.2205	1.2205	1.2205	1.2203"-1.2206"
Piston Bore Diameter	1.2209	1.2209	1.2209	1.2207"-1.2212"
Piston Pin Clearance	0.0004	0.0004	0.0004	0.0003"-0.0012"
Bearing Clerances				
Connecting Rod to Journal	0.002	0.002	0.002	0.0017"-0.0039"
Main Bearing to Journa	0.0015	0.002	0.0019	0.001"-0.005"

Pre-Test Cylinder Bore Measurements, inches

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.0544	4.0545		0.0001
	Middle	4.0546	4.0540	4.0545	0.0006
	Bottom	4.0544	4.0540		0.0004
	Taper	0.0002	0.0005		
2	Top	4.0544	4.0546		0.0002
	Middle	4.0544	4.0543	4.0545	0.0001
	Bottom	4.0545	4.0542		0.0003
	Taper	0.0001	0.0004		
3	Top	4.0548	4.0543		0.0005
	Middle	4.0546	4.0540	4.0546	0.0006
	Bottom	4.0546	4.0543		0.0003
	Taper	0.0002	0.0003		
4	Top	4.0548	4.0541		0.0007
	Middle	4.0546	4.0540	4.0547	0.0006
	Bottom	4.0547	4.0542		0.0005
	Taper	0.0002	0.0002		
5	Top	4.0542	4.0547		0.0005
	Middle	4.0540	4.0542	4.0542	0.0002
	Bottom	4.0544	4.0542		0.0002
	Taper	0.0004	0.0005		
6	Top	4.0542	4.0543		0.0001
	Middle	4.0540	4.0542	4.0541	0.0002
	Bottom	4.0541	4.0549		0.0008
	Taper	0.0002	0.0007		
7	Top	4.0555	4.0552		0.0003
	Middle	4.0554	4.0554	4.0554	0.0000
	Bottom	4.0554	4.0553		0.0001
	Taper	0.0001	0.0002		
8	Top	4.0556	4.0553		0.0003
	Middle	4.0553	4.0558	4.0555	0.0005
	Bottom	4.0556	4.0553		0.0003
	Taper	0.0003	0.0005		

Post-Test Cylinder Bore Measurements, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.0552	4.0550		0.0002
	Middle	4.0550	4.0548	4.0551	0.0002
	Bottom	4.0552	4.0548		0.0004
	Taper	0.0002	0.0002		
2	Top	4.0554	4.0545		0.0009
	Middle	4.0550	4.0547	4.0549	0.0003
	Bottom	4.0548	4.0541		0.0007
	Taper	0.0006	0.0006		
3	Top	4.0553	4.0548		0.0005
	Middle	4.0554	4.0548	4.0554	0.0006
	Bottom	4.0554	4.0548		0.0006
	Taper	0.0001	0.0000		
4	Top	4.0555	4.0551		0.0004
	Middle	4.0552	4.0547	4.0552	0.0005
	Bottom	4.0552	4.0548		0.0004
	Taper	0.0003	0.0004		
5	Top	4.0556	4.0553		0.0003
	Middle	4.0555	4.0547	4.0555	0.0008
	Bottom	4.0555	4.0548		0.0007
	Taper	0.0001	0.0006		
6	Top	4.0557	4.0549		0.0008
	Middle	4.0555	4.0547	4.0556	0.0008
	Bottom	4.0556	4.0546		0.0010
	Taper	0.0002	0.0003		
7	Top	4.0570	4.0555		0.0015
	Middle	4.0570	4.0553	4.0570	0.0017
	Bottom	4.0570	4.0554		0.0016
	Taper	0.0000	0.0002		
8	Top	4.0572	4.0556		0.0016
	Middle	4.0572	4.0554	4.0571	0.0018
	Bottom	4.0570	4.0553		0.0017
	Taper	0.0002	0.0003		

Cylinder Bore Diameter Changes, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. Change (TD@MID + TD@BOT)/2
1	Top	0.0008	0.0005	
	Middle	0.0004	0.0008	0.0006
	Bottom	0.0008	0.0008	
2	Top	0.0010	0.0001	
	Middle	0.0006	0.0004	0.0004
	Bottom	0.0003	0.0001	
3	Top	0.0005	0.0005	
	Middle	0.0008	0.0008	0.0008
	Bottom	0.0008	0.0005	
4	Top	0.0007	0.0010	
	Middle	0.0006	0.0007	0.0006
	Bottom	0.0005	0.0006	
5	Top	0.0014	0.0006	
	Middle	0.0015	0.0005	0.0013
	Bottom	0.0011	0.0006	
6	Top	0.0015	0.0006	
	Middle	0.0015	0.0005	0.0015
	Bottom	0.0015	0.0003	
7	Top	0.0015	0.0003	
	Middle	0.0016	0.0001	0.0016
	Bottom	0.0016	0.0001	
8	Top	0.0016	0.0003	
	Middle	0.0019	0.0004	0.0017
	Bottom	0.0014	0.0000	
Avgerage All Cylinders	Top	0.0011	0.0005	
	Middle	0.0011	0.0005	
	Bottom	0.0010	0.0004	

Piston Skirt to Bore Clearance, in

	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
Pre - Test	1	4.0545	4.0500	0.0045
	2	4.0545	4.0510	0.0034
	3	4.0546	4.0510	0.0036
	4	4.0547	4.0510	0.0037
	5	4.0542	4.0510	0.0032
	6	4.0541	4.0510	0.0031
	7	4.0554	4.0510	0.0044
	8	4.0555	4.0510	0.0045
Post - Test	1	4.0551	4.0490	0.0061
	2	4.0549	4.0500	0.0049
	3	4.0554	4.0500	0.0054
	4	4.0552	4.0495	0.0057
	5	4.0555	4.0500	0.0055
	6	4.0556	4.0500	0.0056
	7	4.0570	4.0500	0.0070
	8	4.0571	4.0490	0.0081

Top and Second Ring Radial Wear, in

Top Ring						Second Ring				
Cylinder	Position	Before	After	Delta		Cylinder	Position	Before	After	Delta
1	1	0.17815	0.17785	0.00030		1	1	0.16190	0.16150	0.00040
	2	0.17930	0.17920	0.00010			2	0.16345	0.16315	0.00030
	3	0.17925	0.17890	0.00035			3	0.16150	0.16090	0.00060
	4	0.17850	0.17820	0.00030			4	0.16045	0.15995	0.00050
	5	0.17855	0.17800	0.00055			5	0.16220	0.16145	0.00075
2	1	0.17890	0.17825	0.00065		2	1	0.16210	0.16165	0.00045
	2	0.17970	0.17925	0.00045			2	0.16355	0.16320	0.00035
	3	0.17830	0.17815	0.00015			3	0.16255	0.16190	0.00065
	4	0.17990	0.17965	0.00025			4	0.16065	0.16050	0.00015
	5	0.17895	0.17875	0.00020			5	0.16195	0.16115	0.00080
3	1	0.17960	0.17890	0.00070		3	1	0.16350	0.16270	0.00080
	2	0.17920	0.17880	0.00040			2	0.16050	0.15985	0.00065
	3	0.17930	0.17895	0.00035			3	0.16110	0.16035	0.00075
	4	0.17865	0.17830	0.00035			4	0.16315	0.16285	0.00030
	5	0.17935	0.17890	0.00045			5	0.16385	0.16330	0.00055
4	1	0.17900	0.17795	0.00105		4	1	0.16175	0.15935	0.00240
	2	0.17950	0.17785	0.00165			2	0.16255	0.16070	0.00185
	3	0.17910	0.17795	0.00115			3	0.16220	0.15980	0.00240
	4	0.17940	0.17800	0.00140			4	0.16200	0.16090	0.00110
	5	0.17865	0.17740	0.00125			5	0.16235	0.16085	0.00150
5	1	0.17970	0.17955	0.00015		5	1	0.16215	0.16135	0.00080
	2	0.17980	0.17945	0.00035			2	0.16405	0.16345	0.00060
	3	0.17900	0.17890	0.00010			3	0.16270	0.16215	0.00055
	4	0.17905	0.17865	0.00040			4	0.16090	0.16070	0.00020
	5	0.17930	0.17885	0.00045			5	0.16130	0.16055	0.00075
6	1	0.17930	0.17890	0.00040		6	1	0.16150	0.16085	0.00065
	2	0.17830	0.17795	0.00035			2	0.16380	0.16315	0.00065
	3	0.17890	0.17795	0.00095			3	0.16150	0.16110	0.00040
	4	0.17890	0.17845	0.00045			4	0.16110	0.16055	0.00055
	5	0.17890	0.17850	0.00040			5	0.16255	0.16175	0.00080
7	1	0.17805	0.17780	0.00025		7	1	0.16240	0.16170	0.00070
	2	0.17840	0.17800	0.00040			2	0.16180	0.16145	0.00035
	3	0.17875	0.17855	0.00020			3	0.16115	0.16065	0.00050
	4	0.17935	0.17895	0.00040			4	0.16130	0.16075	0.00055
	5	0.17880	0.17870	0.00010			5	0.16225	0.16160	0.00065
8	1	0.17950	0.17835	0.00115		8	1	0.16100	0.15995	0.00105
	2	0.17960	0.17895	0.00065			2	0.16080	0.16010	0.00070
	3	0.17930	0.17855	0.00075			3	0.16210	0.16095	0.00115
	4	0.17950	0.17890	0.00060			4	0.16255	0.16200	0.00055
	5	0.17915	0.17865	0.00050			5	0.16120	0.16020	0.00100

Maximum	0.00165		Maximum	0.00240
Average	0.00053		Average	0.00076

Piston Ring Gap Measurements, in

Cylinder	Ring No.	Before	After	Delta
1	1	0.020	0.022	0.002
	2	0.042	0.048	0.006
	3	0.023	0.025	0.002
2	1	0.021	0.024	0.003
	2	0.042	0.048	0.006
	3	0.020	0.024	0.004
3	1	0.021	0.024	0.003
	2	0.041	0.047	0.006
	3	0.022	0.025	0.003
4	1	0.021	0.028	0.007
	2	0.042	0.054	0.012
	3	0.021	0.030	0.009
5	1	0.021	0.024	0.003
	2	0.041	0.048	0.007
	3	0.021	0.024	0.003
6	1	0.022	0.025	0.003
	2	0.041	0.048	0.007
	3	0.021	0.023	0.002
7	1	0.020	0.023	0.003
	2	0.042	0.048	0.006
	3	0.021	0.024	0.003
8	1	0.021	0.027	0.006
	2	0.041	0.049	0.008
	3	0.022	0.024	0.002

Ring No. 1 max increase	0.007
Ring No. 2 max increase	0.012
Ring No. 3 max increase	0.009

Ring No. 1 avg increase	0.004
Ring No. 2 avg increase	0.007
Ring No. 3 avg increase	0.004

Piston Ring Mass, grams

Cylinder	Ring No.	Before	After	Delta
1	1	22.8054	22.6894	0.1160
	2	17.0221	16.9738	0.0483
	3	14.7469	14.7111	0.0358
2	1	22.8125	22.7080	0.1045
	2	17.0221	16.9738	0.0483
	3	14.7469	14.7111	0.0358
3	1	22.9053	22.7253	0.1800
	2	17.1727	17.1133	0.0594
	3	14.6093	14.5648	0.0445
4	1	22.7741	22.1417	0.6324
	2	17.0364	16.8434	0.1930
	3	15.0579	14.9075	0.1504
5	1	22.8351	22.7195	0.1156
	2	17.0065	16.9515	0.0550
	3	15.2000	15.1560	0.0440
6	1	22.7740	22.6587	0.1153
	2	17.0464	16.9897	0.0567
	3	15.0848	15.0075	0.0773
7	1	22.8633	22.7275	0.1358
	2	17.0130	16.9650	0.0480
	3	14.8256	14.7873	0.0383
8	1	22.8472	22.6083	0.2389
	2	17.0351	16.9536	0.0815
	3	15.1805	15.1201	0.0604

Ring No. 1 max decrease	0.6324
Ring No. 2 max decrease	0.1930
Ring No. 3 max decrease	0.1504

Ring No. 1 avg decrease	0.2048
Ring No. 2 avg decrease	0.0738
Ring No. 3 avg decrease	0.0608

Connecting Rod Bearing Weight Loss, grams

Rod Bearing	Shell	Before	After	Change
1	Top	27.6374	27.5924	0.0450
	Bottom	27.6329	27.4935	0.1394
2	Top	27.7361	27.6734	0.0627
	Bottom	27.7891	27.6691	0.1200
3	Top	28.3598	28.3214	0.0384
	Bottom	27.7388	27.5453	0.1935
4	Top	27.7824	27.7493	0.0331
	Bottom	27.6588	27.5888	0.0700
5	Top	28.3864	28.3318	0.0546
	Bottom	27.7195	27.4618	0.2577
6	Top	27.7909	27.6538	0.1371
	Bottom	27.6646	27.3926	0.2720
7	Top	28.4030	28.3497	0.0533
	Bottom	27.7473	27.5859	0.1614
8	Top	27.7947	27.7374	0.0573
	Bottom	27.6362	27.5641	0.0721

Maximum	0.2720
Average	0.1105

Main Bearing Weight Loss, grams

Main Bearing	Shell	Before	After	Change
1	Top	49.0885	49.0308	0.0577
	Bottom	52.6924	52.6180	0.0744
2	Top	49.1857	49.0956	0.0901
	Bottom	52.7295	52.3934	0.3361
3	Top	94.3254	94.1468	0.1786
	Bottom	98.5299	98.3684	0.1615
4	Top	49.1683	49.1044	0.0639
	Bottom	53.3010	53.2234	0.0776
5	Top	69.8869	69.8294	0.0575
	Bottom	73.8082	73.6233	0.1849

Maximum	0.3361
Average	0.1282

Stanadyne Injection Pump Calibration/Evaluation

Pump Type :	**DB2831-5079 (arctic)**			**SN: 14734731**	
Test condition :	6.5L(T) Engine for Endurance Testing, Cell 07			**AL:**	
PUMP RPM	***Description***	***Spec.***	***Pre Test***	***Post Test***	***Change***
1000	Transfer pump psi.	60-62 psi	64	62	-2
	Return Fuel	225-375 cc	340	350	10
350	Low Idle	12-16 cc	16	4	-12
	Housing psi.	8-12 psi	11	9.5	-1.5
	Advance	3.5 deg. min	5	5.53	0.53
	Cold Advance Solenoid	0-1 psi.	0	0.5	0.5
750	Shut-Off	4 cc max.	0.5	0	-0.5
900	Fuel Delivery	66.5 - 69.5cc	67	67	0
1600	WOT Fuel delivery	59.5 min.	63	65	2
	WOT Advance	2.5 - 3.5 deg.	3.5	2.25	-1.25
	Face Cam Fuel delivery	21.5 - 23.5	22	23	1
	Face Cam Advance	5.25 - 7.25 deg.	6.5	8.3	1.8
	Low Idle	11 - 12 deg.	11	11	0
1825	Fuel Delivery	33 cc min.	35	40	5
1950	High Idle	15 cc max.	4	2	-2
	Transfer pump psi.	125 psi max.	107	103	-4
200	WOT Fuel Delivery	58 cc min.	64	63	-1
	WOT Shut-Off	4 cc max.	0	0	0
75	Low Idle Fuel Delivery	37 cc min.	56	53	-3
	Transfer pump psi.	16 psi min.	20	20	0
	Housing psi.	0 -12 psi	9	9	0
	Air Timing	-.5 deg.(+/-.5 deg)	-1	-1	0
	Fluid Temp. Deg. C				
	Date		2/25/2009	8/6/2009	

Photographs

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Piston Skirt Thrust - Best Cyl. 4

Piston Skirt Anti-thrust - Best Cyl. 4

GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Piston Skirt Thrust - Worst Cyl. 1

Piston Skirt Anti-thrust - Worst Cyl. 1

GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Piston Rings - Best Cyl. 2

Piston Rings - Worst Cyl. 4

GEP 6.5L - NATO CYCLE

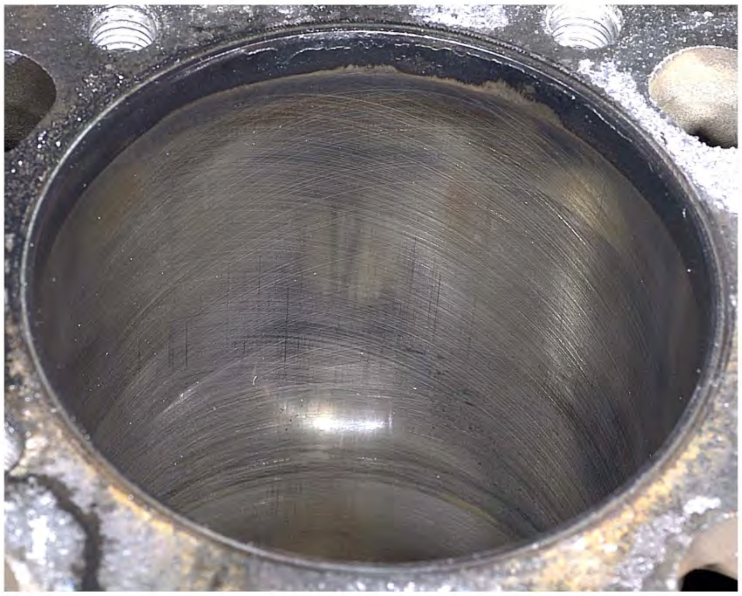
Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Piston Undercrown - Best   Cyl. 4

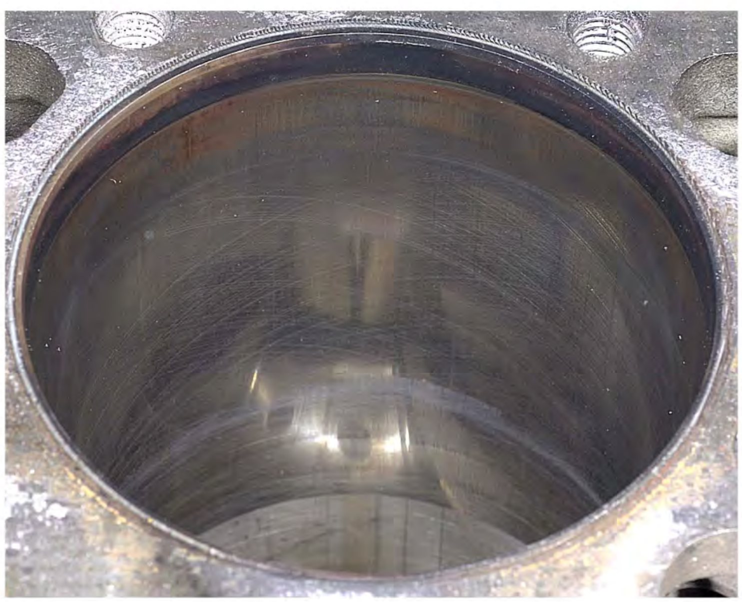
Piston Undercrown - Worst   Cyl. 1

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Engine Block Cylinder Bore - Best Cyl. 5



Engine Block Cylinder Bore - Worst Cyl. 4



GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Exhaust and Intake Valve - Best Cyl. 7

GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Exhaust and Intake Valve - Worst Cyl. 4

GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	EOT Date:	20090727
Test No.:	LO-241026-65T1-NATO-400	Test Length:	400

Rod Bearings

GEP 6.5L - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	20090727
Test No.:	LO-241026-65T1-NATO-400	**Test Length:**	400

Main Bearings

APPENDIX C

Caterpillar C7

Test Number: LO228213-C71-2W-420

Test Procedure: Tactical Wheeled Vehicle

EVALUATION OF MIL-PRF-46167D OEA30 ARCTIC OIL

Work Directive No. 42

Caterpillar C7

Test Lubricant: LO-228213
MIL-PRF-46167D OEA30 Arctic Oil
Test Fuel: JP-8
Test Number: LO228213-C71-2W-420
Start of Test Date: June 21, 2009
End of Test Date: August 27, 2009
Test Duration: 630 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Introduction

This test was used to evaluate MIL-PRF-46167D OEA30 Arctic Oil for use in military tactical vehicles at desert conditions using the procedures outlined in the Tactical Wheeled Vehicle Cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Work Directive 42, Single Common Powertrain Lubricants for Combat/Tactical Equipment.

Test Engine

The experimental oil was evaluated in the Caterpillar (CAT) C7 turbocharged diesel engine, representative of engines currently fielded in the Family of Medium Tactical Vehicles (FMTV), the IAV Stryker, and some Mine Resistant Ambush Protected (MRAP) variants. Prior to testing, the engine was disassembled and measured for pre-test wear. Engine clearances and specifications were verified, and the engine was reassembled following standard assembly procedures.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for CAT engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorbing dynamometer was used to supply engine loading. Engine oil, fuel, and coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers. Engine intake air was supplied at ambient conditions with engine exhaust vented to the atmosphere using the building blower system.

Engine Run-in

Prior to testing, the engine was run-in using the candidate oil following procedures outlined below. The cyclic modes were repeated for a total of 6 cycles, for a total engine run-in runtime of approximately 6 hours.

Time, min	Mode	Speed, RPM	Torque, lb*ft	Coolant Out, °F	Oil Galley, °F
1	Cyclic	750	0	195	210
10	Cyclic	1400	180	190	200
10	Cyclic	1900	175	190	200
10	Cyclic	2400	160	190	205
5	Cyclic	2400	320	190	210
5	Cyclic	1900	350	190	210
5	Cyclic	1400	375	190	205
3	Cyclic	1400	755	190	205
3	Cyclic	1900	750	190	210
3	Cyclic	2400	665	190	215

Figure 1 - Test Engine Run-In Procedure

Pre-Test Engine Performance Check

After completion of engine run-in, a full load powercurve was completed from 1000 rpm to rated engine speed (2400 rpm) to determine pre-test engine performance. The pre-test engine performance check was completed using the same oil charge used during the engine run-in segment. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during oil evaluation was the standard 210 hr Tactical Wheeled Vehicle cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Due to past testing experience gained during CAT C7 testing, the test was scheduled to complete two 210 hr test cycles for a total test time of 420 hrs due to the engines traditionally low impact on oil condition. Test termination would occur at 420 hrs or upon major oil degradation, which ever occurred first. The test cycle consists of cyclic modes alternating between 2 hr rated speed conditions and 1 hr idle soaks. Total daily run-time was 14 hrs, 10 hrs at rated and 4 hrs at idle, with a 10 hr soak overnight before resuming the next days testing. Engine oil and coolant temperatures were elevated to simulate conditions consistent with desert warfare use. Engine operating parameters were controlled through out testing as specified in the table below. (Note – The CAT C7 has an integral oil cooler built into the engine block that is cooled by the engine coolant. Due to this, the oil sump temperature of the CAT C7 engine cannot directly be controlled. To achieve the desired oil sump temperature, the water jacket temperature was modified to achieve the oil sump target.) Engine coolant was a 60/40 blend of ethylene glycol antifreeze and deionized water. Test fuel was JP-8.

Parameter	Rated Speed	Idle
Engine Speed, RPM	2400 +/- 25	750 +/- 25
Water Jacket Out, °F	223.5 +/- 3	110 +/- 3
Oil Sump, °F	260*	130*
*Oil sump temperature is not controlled. Water jacket temperature is manipulated to achieve desired sump temperature		

Figure 2 - Test Cycle Operating Parameters

Over the course of testing it was noticed that oil condition remained very consistent, and showed little signs of degradation as the test continued. Near the completion of 420 hrs it was decided to continue testing past the scheduled end of test (EOT) to help determine extended drain interval properties of the candidate oil. The extended testing was to continue until 630 hrs, or upon degradation of oil condition. The testing continued until the 630 hr termination point, for a total of three 210 hr test cycles. The oil was still in good condition at the close of testing, retaining a stable TBN reserve with minimal wear metals present in the charge.

Oil Sampling

Eight ounces of engine oil was sampled every 14 hrs for used oil analysis. Engine oil analysis consisted of the following tests: (Note – at every 70 hr interval, two additional tests were completed on the used oil as shown below). All oil samples were weighed and logged to take into account during calculations of total engine oil consumption for the test duration.

Every 14hrs		
ASTM	**D4739**	Total Base Number
ASTM	**D664**	Total Acid Number
ASTM	**D445**	Kinematic Viscosity @ 100°C
ASTM	**API Gravity**	API Gravity
ASTM	**D4052**	Density
ASTM	**TGA SOOT**	TGA Soot
ASTM	**E168**	Oxidation
ASTM	**E168**	Nitration
ASTM	**D5185**	Wear Metals by ICP

Every 70hrs		
ASTM	**D445**	Kinematic Viscosity @ 40°C
ASTM	**D2270**	Kinematic Viscosity Index

Figure 3 - Used Oil Analysis Procedures

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily and replenished as needed to restore oil level to full mark. This process occurred daily after the completion of the 10 hr soak prior to restarting testing the next day. All oil additions were weighed and logged to take into account during calculation of total engine oil consumption for the test duration.

Post-Test Engine Performance Check

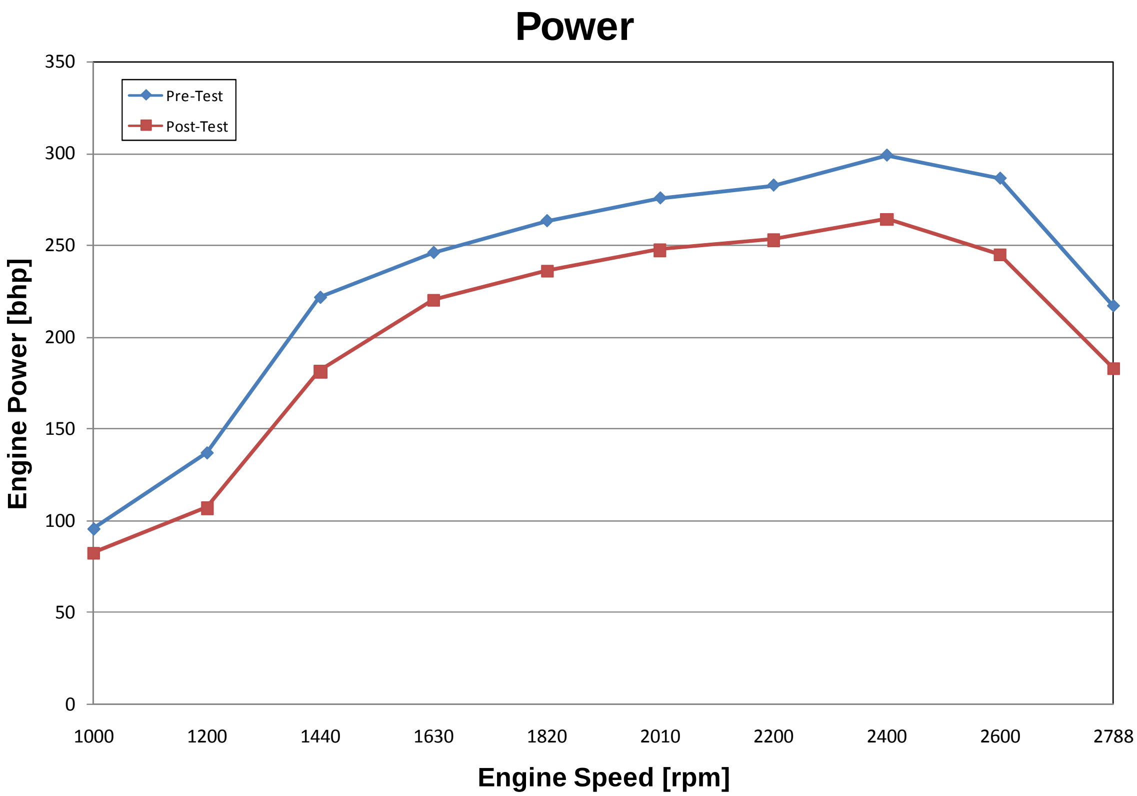
After completion of testing, a full load powercurve was completed from 1000 rpm to rated engine speed (2400rpm) to determine post-test engine performance. The post-test engine performance check was completed using the same oil charge used during the testing segment. Powercurve plots can be seen in the Engine Performance Curves section.

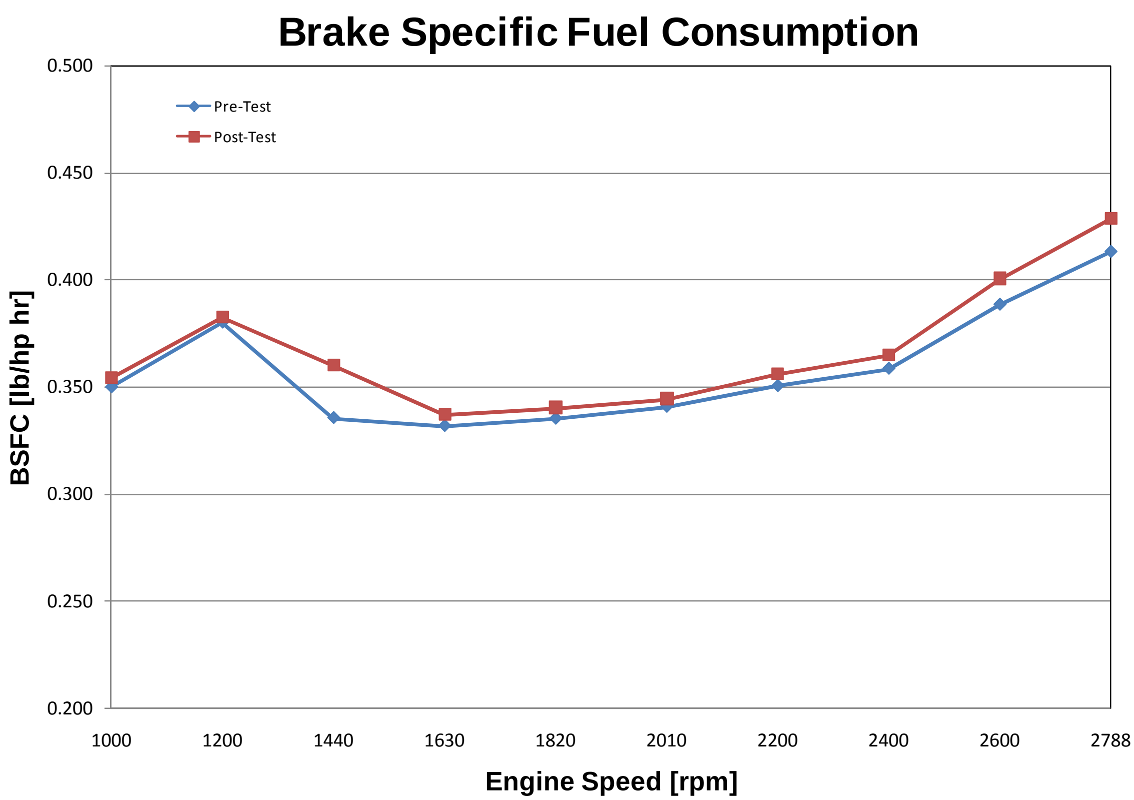
Engine Operating Conditions Summary

Below is a summary of the engine operating conditions over the duration of the 210 engine running hours.

		Rated Conditions (2400 RPM)		Idle Conditions (750 RPM)	
Perameter:	**Units:**	Average	Std. Dev.	Average	Std. Dev.
Engine Speed	*RPM*	2400.0	1.0	750.2	6.2
Torque*	*ft*lb*	618.0	21.7	4.3	10.1
Fuel Flow	*lb/hr*	101.0	10.5	2.8	0.8
Power*	*bhp*	282.4	9.9	0.6	1.9
BSFC*	*lb/bhp*hr*	0.358	0.036	**	**
Temperatures:					
Coolant In	*°F*	212.1	0.7	101.9	2.5
Coolant Out	*°F*	223.5	0.6	109.8	1.4
Oil Sump	*°F*	259.1	1.8	130.2	8.8
Fuel In	*°F*	116.4	5.3	100.7	8.4
Inlet Air	*°F*	102.8	5.9	93.0	4.3
Intake Manifold Air	*°F*	140.0	4.6	83.6	1.4
Cylinder 1 Exhaust	*°F*	971.1	27.2	174.9	4.5
Cylinder 2 Exhaust	*°F*	1097.6	21.4	185.0	4.1
Cylinder 3 Exhaust	*°F*	1074.4	28.4	198.2	4.5
Cylinder 4 Exhaust	*°F*	1025.6	16.6	194.5	4.6
Cylinder 5 Exhaust	*°F*	1045.1	22.4	184.5	4.1
Cylinder 6 Exhaust	*°F*	936.7	35.3	180.5	5.3
Exhaust Before Turbo, Front	*°F*	1129.5	28.2	200.9	20.0
Exhaust Before Turbo, Rear	*°F*	1065.2	45.2	198.9	13.5
Exhaust After Turbo	*°F*	851.3	26.7	197.2	23.0
Pressures:					
Oil Galley	*psi*	35.9	1.7	37.7	2.8
Ambient Pressure	*psiA*	14.2	0.1	14.2	0.1
Intake Before Compressor	*psiA*	13.6	0.0	14.3	0.0
Intake After Compressor	*psiA*	42.7	0.1	14.4	0.1
Boost	*psi*	29.0	0.1	0.1	0.1
Exahust Stack	*psi*	0.3	0.0	-0.2	0.0

Engine Performance Curves





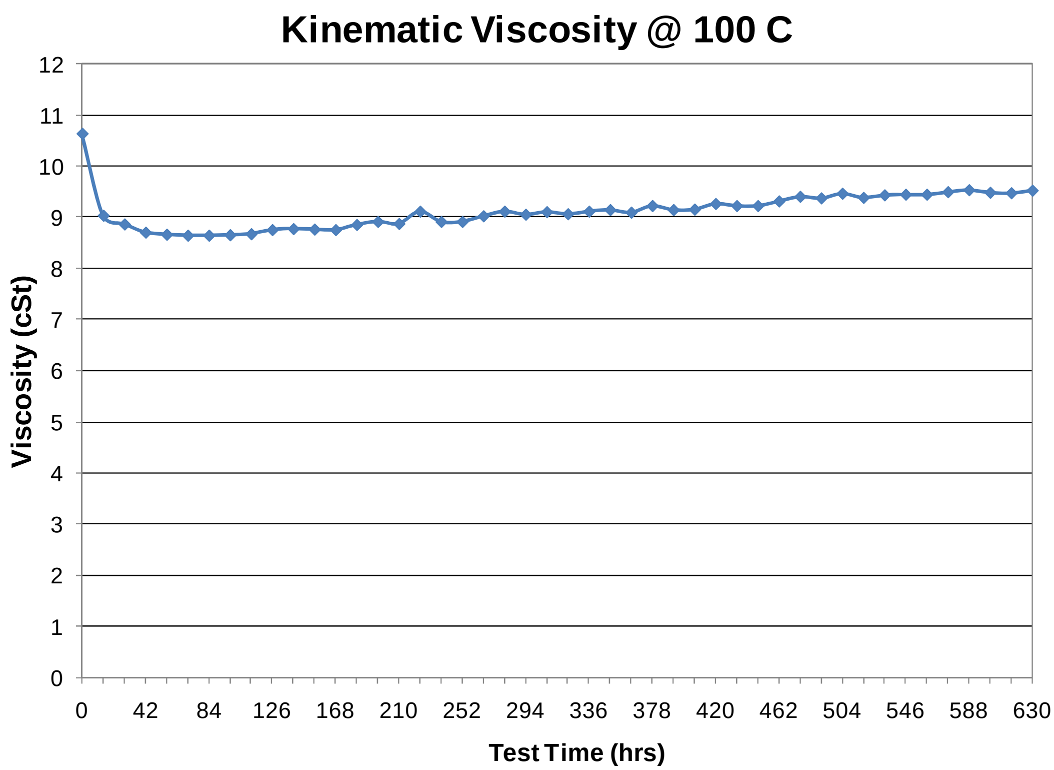
Engine Oil Analysis

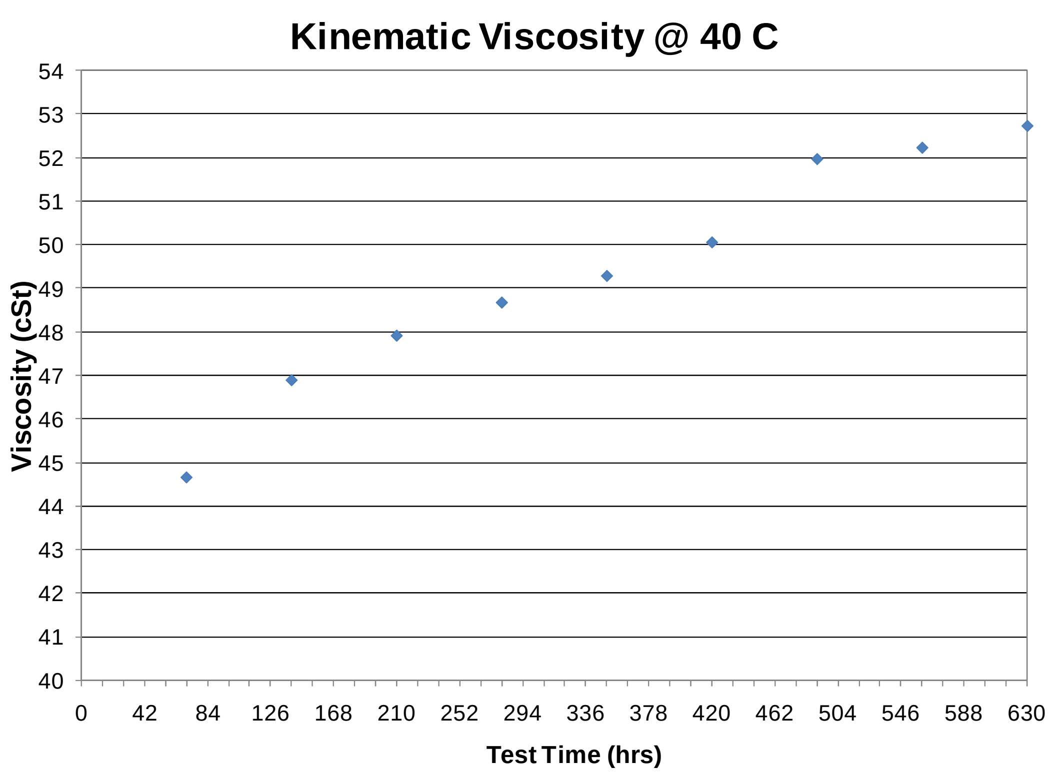
Property	ASTM Test	Test Hours															
		0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210
Density (g/mL)	D4052	0.8493	0.8495	0.8496	0.85	0.8502	0.8504	0.8507	0.8511	0.8525	0.8516	0.8517	0.852	0.8523	0.8525	0.8528	0.853
Viscosity @ 100°C (cSt)	D445	10.63	9.03	8.86	8.7	8.66	8.64	8.64	8.65	8.67	8.75	8.77	8.76	8.75	8.85	8.91	8.87
Viscosity @ 40°C (cSt)	D445						44.66					46.89					47.91
Viscosity Index (dyne/cm)	D2270						176					169					168
Total Base Number (mg KOH/g)	D4739	10.29	9.62	9.1	8.42	7.6	7.82	7.3	6.81	6.79	6.77	6.12	5.99	6.19	5.8	5.81	5.84
Total Acid Number (mg KOH/g)	D664	2.67	2.7	2.8	3.07	2.9	3.08	3.16	3.19	3.07	2.95	3.23	3.51	2.98	3.11	3	2.9
Oxidation (Abs./cm)	E168 FTNG	0	-0.95	-0.99	-0.37	0.09	0.65	1.29	2.03	2.4	3.05	3.32	3.7	4.07	4.54	4.72	5.28
Nitration (Abs./cm)	E168 FTNG	0	0.37	0.37	0.46	0.55	0.55	0.55	0.55	0.55	0.55	0.46	0.46	0.65	0.37	0.56	0.37
Soot	Soot	0.111	0.145	0.197	0.198	0.266	0.248	0.348	0.318	0.301	0.343	0.406	0.4	0.388	0.441	0.438	0.513
Wear Metals (ppm)	D5185																
Al		1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		3	2	<1	4	2	1	3	1	3	2	2	2	2	1	6	<1
Ca		3512	3611	3598	3617	3685	3619	3737	3749	3807	3750	3843	3841	3798	3772	3790	3842
Cr		<1	<1	<1	<1	<1	<1	1	1	1	1	1	2	2	2	2	2
Cu		<1	2	3	4	4	4	4	5	6	7	7	8	9	9	9	9
Fe		2	6	8	10	12	14	16	18	20	22	23	26	28	29	32	33
Pb		<1	<1	1	2	1	2	2	2	2	2	2	2	3	2	3	4
Mg		14	13	16	14	16	14	15	16	16	15	15	15	15	16	15	16
Mn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mo		<1	<1	<1	<1	1	<1	<1	<1	<1	1	1	<1	1	<1	<1	<1
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1302	1270	1236	1241	1218	1187	1194	1183	1184	1160	1189	1181	1186	1177	1169	1182
Si		3	6	6	7	8	6	8	9	8	9	9	10	10	10	9	9
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	5	<5	5	5	<5	5	5	5	5	5	5	6	5	5	6
Sn		<1	<1	<1	<1	<1	<1	1	1	1	2	2	1	2	2	2	2
Zn		1510	1521	1498	1507	1492	1460	1463	1477	1480	1475	1480	1482	1496	1491	1503	1511
K		8	6	<5	<5	5	<5	<5	<5	<5	6	<5	5	<5	<5	<5	<5
Sr		1	<1	1	<1	1	1	<1	<1	<1	<1	<1	<1	<1	1	<1	1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

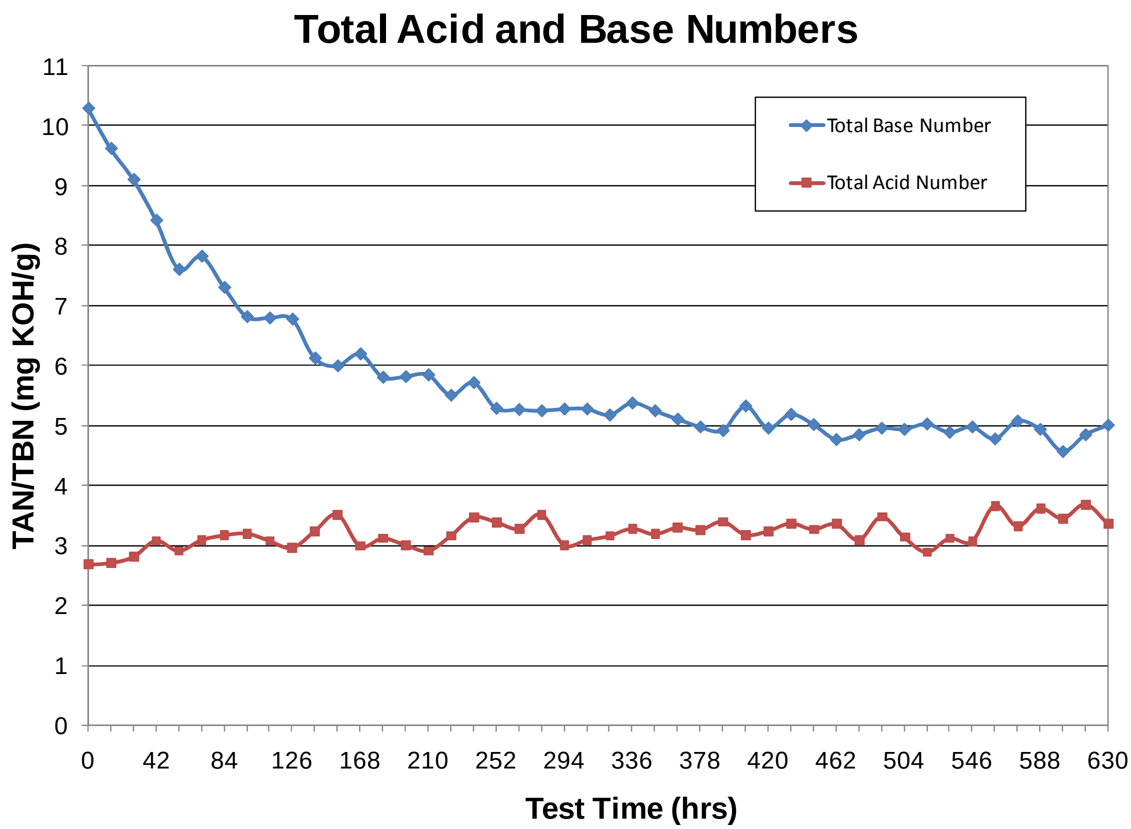
Property	ASTM Test	Test Hours														
		224	238	252	266	280	294	308	322	336	350	364	378	392	406	420
Density (g/mL)	D4052	0.8531	0.8533	0.8535	0.8537	0.854	0.8541	0.8543	0.8545	0.8546	0.8548	0.8549	0.855	0.8552	0.8553	0.8554
Viscosity @ 100°C (cSt)	D445	9.11	8.91	8.91	9.02	9.11	9.05	9.1	9.06	9.11	9.14	9.09	9.22	9.14	9.15	9.26
Viscosity @ 40°C (cSt)	D445					48.67					49.28					50.05
Viscosity Index (dyne/cm)	D2270					172					170					170
Total Base Number (mg KOH/g)	D4739	5.5	5.71	5.28	5.26	5.24	5.27	5.27	5.17	5.37	5.24	5.1	4.97	4.91	5.32	4.95
Total Acid Number (mg KOH/g)	D664	3.15	3.46	3.38	3.27	3.51	3	3.08	3.15	3.27	3.18	3.29	3.25	3.39	3.17	3.23
Oxidation (Abs./cm)	E168 FTNG	5.37	5.65	6.02	6.48	6.76	7.04	7.31	7.41	7.59	7.96	8.24	8.33	8.52	8.7	9.07
Nitration (Abs./cm)	E168 FTNG	0.37	0.37	0.28	0.19	0.28	0.28	0.37	0.37	0.46	0.28	0.19	0.19	0.19	0.19	0.19
Soot	Soot	0.521	0.522	0.463	0.599	0.602	0.641	0.645	0.658	0.668	0.588	0.708	0.624	0.641	0.679	0.655
Wear Metals (ppm)	D5185															
Al		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		2	<1	3	2	<1	1	<1	1	6	2	<1	2	5	4	1
Ca		3915	3963	3951	4008	3911	3942	4026	3900	4180	4140	3954	4105	4154	4089	3996
Cr		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Cu		9	9	10	10	10	10	10	10	10	10	10	11	11	11	11
Fe		35	37	38	40	42	42	45	47	48	50	52	53	55	57	60
Pb		3	4	4	4	4	4	4	4	5	4	5	4	5	4	5
Mg		16	16	16	19	16	16	14	16	17	16	16	16	16	17	17
Mn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mo		<1	<1	1	<1	<1	<1	1	<1	<1	1	1	1	<1	1	<1
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1169	1187	1176	1175	1202	1153	1201	1203	1224	1209	1210	1247	1205	1250	1257
Si		8	8	10	10	8	10	9	9	10	10	8	10	9	10	10
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		6	<5	5	5	5	6	<5	6	5	5	5	5	5	5	5
Sn		2	2	2	2	2	2	2	2	2	2	2	2	2	2	3
Zn		1510	1516	1553	1548	1542	1569	1551	1567	1599	1600	1585	1608	1612	1625	1634
K		<5	<5	<5	<5	<5	<5	<5	<5	<5	5	<5	<5	<5	5	<5
Sr		2	2	1	1	2	1	2	2	1	1	2	<1	1	1	1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

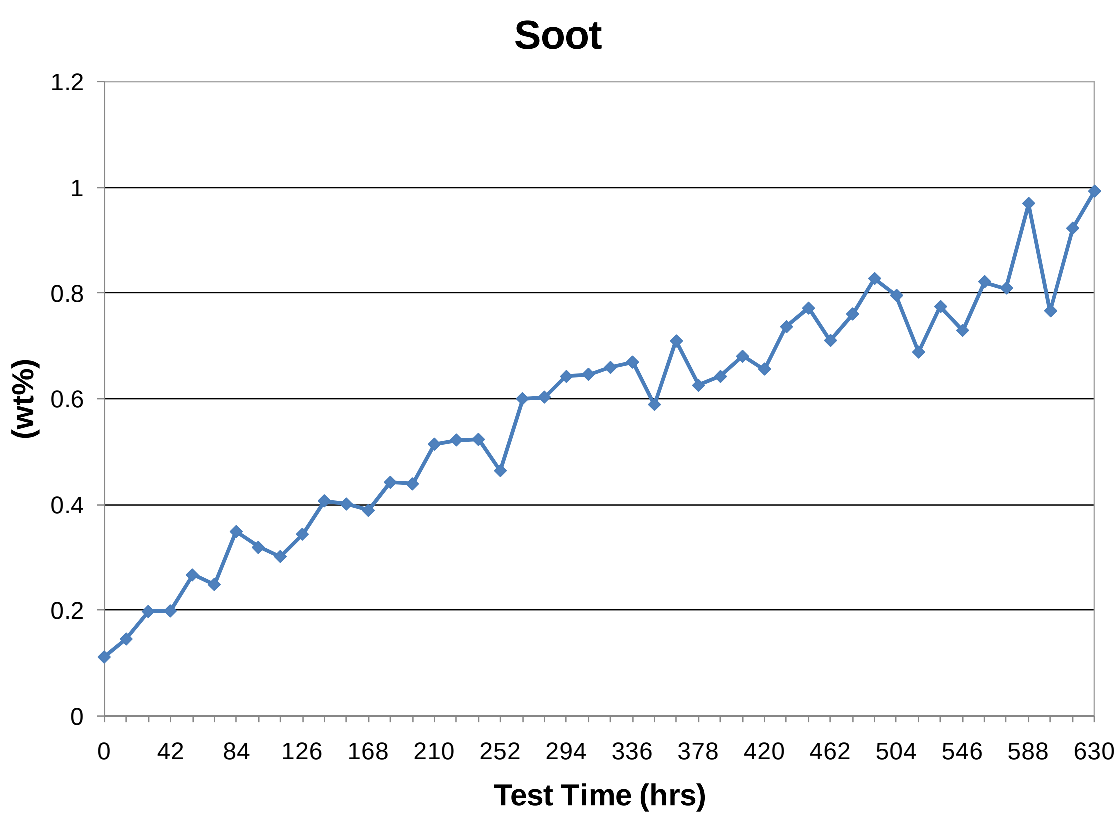
Property	ASTM Test	Test Hours														
		434	448	462	476	490	504	518	532	546	560	574	588	602	616	630
Density (g/mL)	D4052	0.8555	0.8556	0.8574	0.8575	0.8576	0.8576	0.8576	0.8577	0.8578	0.8579	0.858	0.8581	0.8582	0.8582	0.8581
Viscosity @ 100°C (cSt)	D445	9.22	9.22	9.31	9.4	9.37	9.46	9.38	9.43	9.44	9.44	9.49	9.53	9.48	9.47	9.52
Viscosity @ 40°C (cSt)	D445					51.96					52.22					52.72
Viscosity Index (dyne/cm)	D2270					165					166					167
Total Base Number (mg KOH/g)	D4739	5.18	5.01	4.76	4.84	4.95	4.93	5.02	4.88	4.97	4.77	5.07	4.93	4.56	4.84	5
Total Acid Number (mg KOH/g)	D664	3.36	3.26	3.35	3.08	3.47	3.13	2.88	3.11	3.06	3.66	3.31	3.61	3.44	3.68	3.35
Oxidation (Abs./cm)	E168 FTNG	9.26	9.54	8.89	8.96	9.24	9.33	9.43	9.89	10.63	10.63	10.81	10.72	11.09	11.37	11.28
Nitration (Abs./cm)	E168 FTNG	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.28
Soot	Soot	0.735	0.77	0.709	0.759	0.826	0.794	0.687	0.773	0.728	0.82	0.808	0.968	0.765	0.921	0.991
Wear Metals (ppm)	D5185															
Al		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		2	2	4	1	2	2	2	1	3	3	1	2	3	<1	2
Ca		4073	4082	4075	4039	4110	4333	4263	4172	4175	4172	4240	4226	4286	4232	4292
Cr		2	2	3	2	3	2	2	3	3	3	3	3	3	3	2
Cu		11	11	11	11	12	12	11	12	12	12	12	12	12	12	12
Fe		60	63	62	63	64	67	64	67	68	70	70	71	72	72	71
Pb		5	6	6	5	5	5	6	6	6	6	6	7	7	7	7
Mg		17	18	16	16	16	17	16	17	17	17	18	17	18	18	17
Mn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	3	<1
Mo		1	1	<1	1	2	1	1	1	1	<1	1	1	1	1	<1
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1241	1265	1257	1263	1269	1266	1243	1271	1279	1278	1308	1290	1324	1311	1322
Si		9	10	10	10	10	8	10	8	10	10	9	10	10	9	10
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	5	5	5	5	<5	<5	5	5	5	5	5	5	5	5
Sn		2	2	2	2	3	2	2	2	3	3	3	2	3	3	2
Zn		1638	1648	1630	1642	1669	1666	1636	1666	1687	1678	1702	1712	1711	1699	1723
K		<5	<5	<5	<5	5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr		1	2	2	1	1	2	<1	2	1	2	1	1	1	2	1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

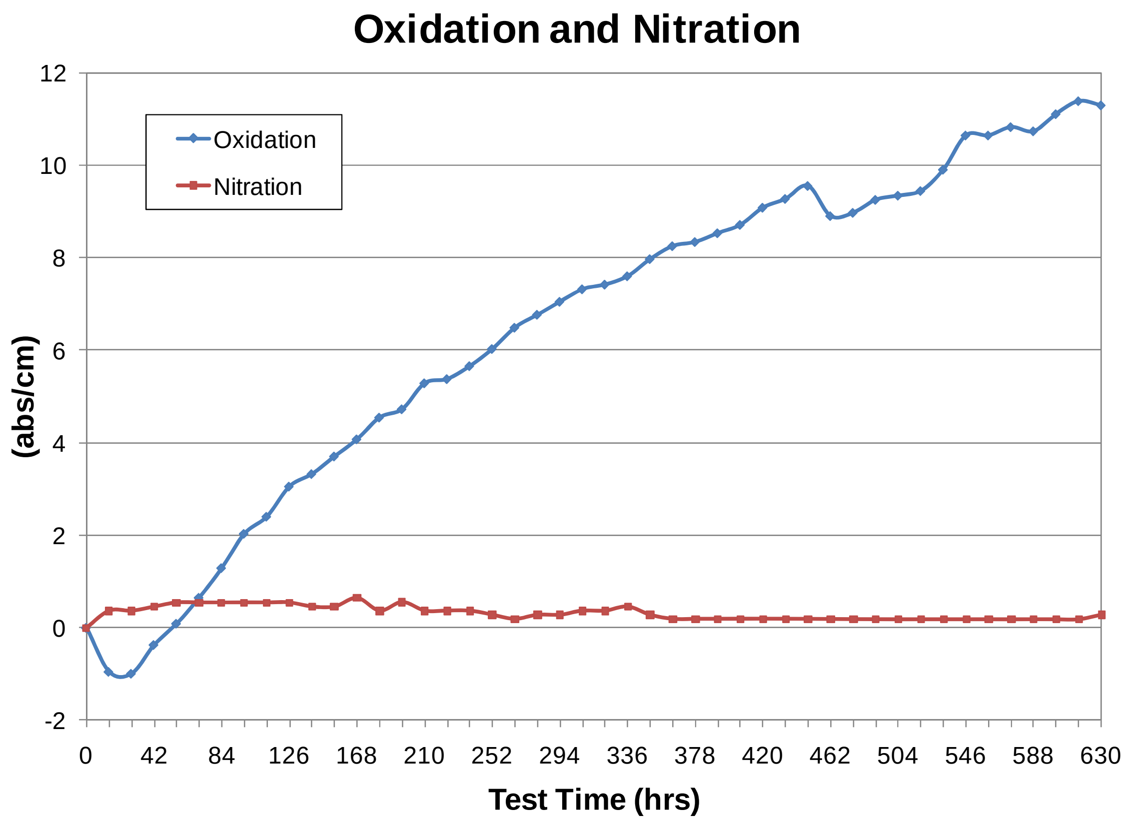
Engine Oil Analysis Trends



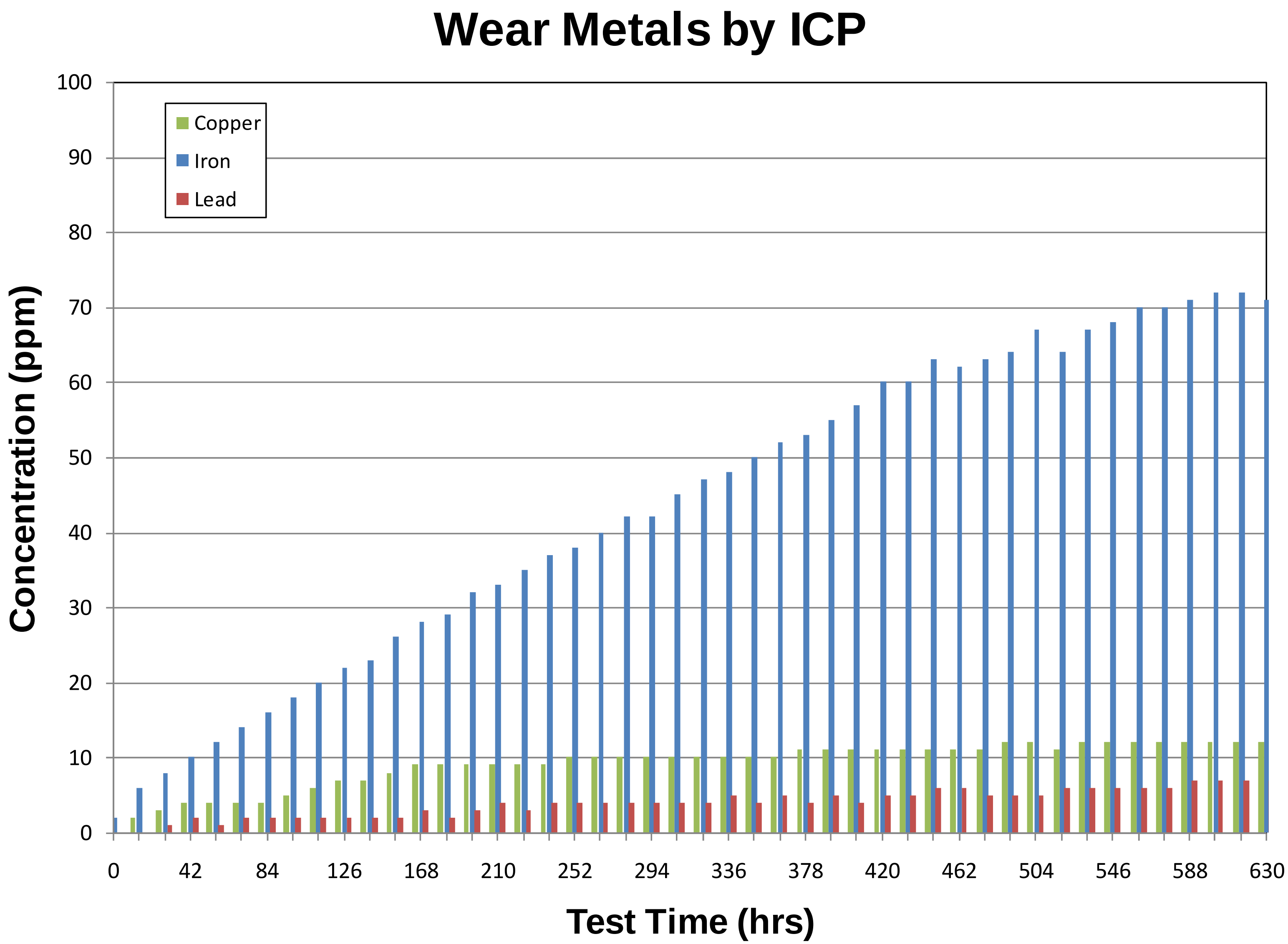



Total Acid and Base Numbers
TAN/TBN (mg KOH/g)
Test Time (hrs)
Total Base Number
Total Acid Number
0
1
2
3
4
5
6
7
8
9
10
11
0 42 84 126 168 210 252 294 336 378 420 462 504 546 588 630


Soot
(wt%)
Test Time (hrs)
0
0.2
0.4
0.6
0.8
1
1.2
0 42 84 126 168 210 252 294 336 378 420 462 504 546 588 630



Oxidation and Nitration
Oxidation
Nitration
(abs/cm)
Test Time (hrs)
12
10
8
6
4
2
0
-2
0
42
84
126
168
210
252
294
336
378
420
462
504
546
588
630


Wear Metals by ICP
Copper
Iron
Lead
100
90
80
70
60
50
40
30
20
10
0
Concentration (ppm)
0
42
84
126
168
210
252
294
336
378
420
462
504
546
588
630
Test Time (hrs)

Oil Consumption Data

Average oil consumption per test hour was 0.070 lbs/hr.

	Additions (lbs)	Samples (lbs)	Consumption (lbs)	Cosumption Accumulated
14-hr	0.7	0.47	0.23	0.23
28-hr	0.7	0.46	0.24	0.47
42-hr	0.92	0.41	0.51	0.98
56-hr	1.14	0.43	0.71	1.69
70-hr	1.65	0.42	1.23	2.92
71-hr	*0.77*	*0*	*0.77*	*3.69*
84-hr	0.6	0.41	0.19	3.88
98-hr	1.64	0.42	1.22	5.1
112-hr	1.14	0.61	0.53	5.63
126-hr	1.61	0.43	1.18	6.81
140-hr	1.42	0.45	0.97	7.78
154-hr	1.28	0.47	0.81	8.59
168-hr	1.18	0.49	0.69	9.28
182-hr	1.25	0.49	0.76	10.04
196-hr	1.2	0.51	0.69	10.73
210-hr	1.66	0.49	1.17	11.9
224-hr	1.41	0.49	0.92	12.82
238-hr	1.3	0.51	0.79	13.61
252-hr	1.35	0.52	0.83	14.44
266-hr	1.28	0.51	0.77	15.21
280-hr	1	0.51	0.49	15.7
294-hr	1.1	0.52	0.58	16.28
308-hr	1.25	0.52	0.73	17.01
322-hr	1.3	0.48	0.82	17.83
336-hr	1.23	0.5	0.73	18.56
350-hr	1.32	0.49	0.83	19.39
364-hr	1.4	0.44	0.96	20.35
378-hr	1.05	0.47	0.58	20.93
392-hr	1.12	0.47	0.65	21.58
406-hr	1.02	0.48	0.54	22.12
420-hr	1.35	0.5	0.85	22.97
434-hr	1.37	0.51	0.86	23.83
448-hr	1.87	0.51	1.36	25.19
462-hr	1.62	0.49	1.13	26.32
476-hr	1.72	0.5	1.22	27.54
490-hr	1.74	0.48	1.26	28.8
504-hr	1.86	0.51	1.35	30.15
518-hr	1.34	0.51	0.83	30.98
532-hr	1.4	0.51	0.89	31.87
546-hr	1.7	0.51	1.19	33.06
560-hr	1.67	0.5	1.17	34.23
574-hr	1.65	0.5	1.15	35.38
588-hr	1.57	0.5	1.07	36.45
602-hr	1.87	0.5	1.37	37.82
616-hr	2.14	0.51	1.63	39.45
630-hr	2.26	0.51	1.75	41.2

Initial Fill	37.71	**Total Additions**	63.12
EOT Drain	34.54	**Total Samples**	21.92

(Initial Fill + Additions)	100.83
(EOT Drain + Samples)	56.46
Total Oil Consumption	44.37

List of Engine Shutdowns and Corrective Action

TOD	Shutdown Failure	Corrective Action
6/24/2009 00:54	Sump Float Moving Average Limit @ Rated	Tuned shutdown limits
6/26/2009 09:31	Sump Float Moving Average Limit @ Rated	Tuned shutdown limits
6/29/2009 23:44	Sump Float Moving Average Limit @ Rated	Tuned shutdown limits
6/30/2009 06:45	No Dyno Water Flow	Building Cooling Tower Down, Replaced Sump Pump
6/30/2009 14:10	TEXHCYL4 < 700°F	Replaced Fuel Injector, Update Trim Code, Restarted
7/6/2009 13:26	TEXHCYL3 >1200°F	Replaced Fuel Injector, Update Trim Code, Restarted
7/7/2009 06:30	Low Sump Float Value @ Idle	Tuned shutdown limits
7/8/2009 03:43	Low Sump Float Value @ Idle	Tuned shutdown limits
7/8/2009 08:15	Sump Float Moving Average Limit @ Rated	Tuned shutdown limits
7/8/2009 10:56	Sump Float Moving Average Limit @ Rated	Tuned shutdown limits
7/8/2009 11:20	Sump Float Moving Average Limit @ Rated	Changed Oil Sump Limits to activate on timer (>1sec)
7/9/2009 06:25	Float Timer Tripped @ Rated	Changed Sump Timer Limits (>2sec)
7/9/2009 06:31	Float Timer Tripped @ Rated	Still triggered off of limits removed from program. PRISM patch installed by development team to repair erroneous limit issus. Changed Sump Timer Limit (>5sec)
7/9/2009 06:34	Float Timer Tripped @ Rated	
7/9/2009 07:23	Sump Float Moving Average Limit	
7/30/2009 10:58	TEXHCYL5 < 700°F	Checked data log, lost fuel flow @ rated, tank farm pump tripped, restarted
8/6/2009 11:27	Float Timer Tripped @ Rated	Found sump float instrumentation wire burned on exahust, repaired
8/14/2009 8:50	MA_DISMP value limit	Limit not set in test instance. PRISM development team updated program version to prevent erroneous limit issues.

Post Test Engine Ratings

Ratings	Clyinder Number						
	1	2	3	4	5	6	Avg
Ring Sticking							
Ring No.1	No	No	No	No	No	No	--
Ring No.2	No	No	Yes	No	No	No	--
Ring No.3	No	No	No	No	No	No	--
Scuffing % Area							
Ring No.1	0	0	0	0	0	0	0.00
Ring No.2	0	0	0	0	0	0	0.00
Ring No.3	0	0	0	0	0	0	0.00
Piston Crown	0	0	0	0	0	0	0.00
Piston Skirt	0	0	0	0	0	0	0.00
Cylinder Liner, %	0	0	0	0	0	0	0.00
Piston Carbon, Demerits							
No.1 Groove	60.75	36.00	27.75	44.00	40.50	59.00	44.67
No.2 Groove	2.00	3.50	5.75	3.50	2.25	2.50	3.25
No.3 Groove	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No.1 Land	39.25	41.25	34.25	36.50	40.25	63.50	42.50
No.2 Land	42.00	31.00	40.50	28.25	2.50	24.50	28.13
No.3 Land	0.00	0.50	2.50	2.00	0.00	1.75	1.13
No.4 Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Piston Lacquer, Demerits							
No.1 Groove	0.00	0.18	0.00	0.03	0.00	0.00	0.04
No.2 Groove	4.80	4.71	4.13	3.05	3.30	2.91	3.82
No.3 Groove	3.17	3.47	3.10	3.56	4.32	3.02	3.44
No.1 Land	0.00	0.00	0.01	0.14	0.02	0.01	0.03
No.2 Land	0.86	0.76	0.27	0.94	2.62	1.57	1.17
No.3 Land	3.64	3.66	2.79	2.65	3.50	2.29	3.09
No.4 Land	3.01	2.18	3.31	2.99	2.84	2.70	2.84
Under Crown	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Total, Demerits	160.98	128.71	125.86	129.11	103.60	165.25	135.59
Miscellanous							
Top Groove Fill, %	50	18	13	40	25	53	33.17
Intermediate Groove Fill, %	0	1	1	0	0	0	0.33
Top Land Heavy Carbon, %	19	22	13	16	21	52	23.83
Top Lan Flaked Carbon, %	0	1	0	2	0	0	0.50
Valve Tulip Deposits, Merits							
Exahust	8.5	8.6	9.0	8.9	8.9	9.0	8.82
Intake, Front	8.8	9.1	9.4	8.9	9.0	9.1	9.05
Intake, Rear	8.2	9.0	9.4	8.8	9.2	9.3	8.98
Intake, Average	8.5	9.1	9.4	8.9	9.1	9.2	9.02

Engine Measurement Changes

Engine Rebuild Measurements, inches

Cylinder Bore	Minimum	Maximum	Average	Spec:
Inside Diameter	4.3313	4.3319	4.3316	4.3307"-4.3327"
Out of Round	0.0001	0.0076	0.0040	Maximum 0.0010"
Taper	0.0005	0.0078	0.0026	
Piston Skirt Diameter	4.3274	4.3286	4.3280	
Piston Skirt to Cylinder Bore Clearance	0.0027	0.0043	0.0036	0.0020"-0.0050"
Ring To Groove Clearance				
Oil Control Ring	0.003	0.003	0.003	
Piston Pin				
Piston Pin Diameter	1.5744	1.5744	1.5744	1.5743"-1.5747"
Piston Bore Diameter	1.5758	1.5760	1.5760	1.5757"-1.5763"
Piston Pin Clearance	0.0014	0.0016	0.0016	0.0010"-0.0040"
Bearing Clerances				
Connecting Rod to Journal	0.003	0.030	0.007	0.0021"-0.0061"
Main Bearing to Journa	0.003	0.004	0.004	0.0028"-0.0068"

Pre-Test Cylinder Bore Measurements, inches

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.3319	4.3313		0.0006
	Middle	4.3316	4.3313	4.3315	0.0003
	Bottom	4.3314	4.3320		0.0006
	Taper	0.0005	0.0007		
2	Top	4.3324	4.3370		0.0046
	Middle	4.3322	4.3390	4.3319	0.0068
	Bottom	4.3315	4.3314		0.0001
	Taper	0.0009	0.0076		
3	Top	4.3322	4.3311		0.0011
	Middle	4.3320	4.3380	4.3318	0.0060
	Bottom	4.3315	4.3310		0.0005
	Taper	0.0007	0.0070		
4	Top	4.3319	4.3380		0.0061
	Middle	4.3317	4.3370	4.3316	0.0053
	Bottom	4.3314	4.3390		0.0076
	Taper	0.0005	0.0020		
5	Top	4.3321	4.3390		0.0069
	Middle	4.3319	4.3390	4.3317	0.0071
	Bottom	4.3314	4.3370		0.0056
	Taper	0.0007	0.0020		
6	Top	4.3321	4.3380		0.0059
	Middle	4.3315	4.3390	4.3313	0.0075
	Bottom	4.3310	4.3312		0.0002
	Taper	0.0011	0.0078		

Post-Test Cylinder Bore Measurements, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.3317	4.3322		0.0005
	Middle	4.3319	4.3325	4.3321	0.0006
	Bottom	4.3322	4.3322		0.0000
	Taper	0.0005	0.0003		
2	Top	4.3319	4.3325		0.0006
	Middle	4.3322	4.3334	4.3320	0.0012
	Bottom	4.3318	4.3328		0.0010
	Taper	0.0004	0.0009		
3	Top	4.3322	4.3325		0.0003
	Middle	4.3320	4.3333	4.3320	0.0013
	Bottom	4.3319	4.3328		0.0009
	Taper	0.0003	0.0008		
4	Top	4.3318	4.3322		0.0004
	Middle	4.3317	4.3327	4.3318	0.0010
	Bottom	4.3318	4.3324		0.0006
	Taper	0.0001	0.0005		
5	Top	4.3321	4.3324		0.0003
	Middle	4.3319	4.3329	4.3318	0.0010
	Bottom	4.3317	4.3325		0.0008
	Taper	0.0004	0.0005		
6	Top	4.3321	4.3319		0.0002
	Middle	4.3318	4.3322	4.3320	0.0004
	Bottom	4.3321	4.3320		0.0001
	Taper	0.0003	0.0003		

Cylinder Bore Diameter Changes, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. Change (TD@MID + TD@BOT)/2
1	Top	0.0002	0.0009	
	Middle	0.0003	0.0012	0.0006
	Bottom	0.0008	0.0002	
2	Top	0.0005	0.0045	
	Middle	0.0000	0.0056	0.0002
	Bottom	0.0003	0.0014	
3	Top	0.0000	0.0014	
	Middle	0.0000	0.0047	0.0002
	Bottom	0.0004	0.0018	
4	Top	0.0001	0.0058	
	Middle	0.0000	0.0043	0.0002
	Bottom	0.0004	0.0066	
5	Top	0.0000	0.0066	
	Middle	0.0000	0.0061	0.0001
	Bottom	0.0003	0.0045	
6	Top	0.0000	0.0061	
	Middle	0.0003	0.0068	0.0007
	Bottom	0.0011	0.0008	
Avgerage All Cylinders	Top	0.0001	0.0042	
	Middle	0.0001	0.0048	
	Bottom	0.0005	0.0025	

Piston Skirt to Bore Clearance, in

	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
Pre - Test	1	4.3315	4.3282	0.0033
	2	4.3319	4.3284	0.0034
	3	4.3318	4.3274	0.0043
	4	4.3316	4.3274	0.0042
	5	4.3317	4.3280	0.0036
	6	4.3313	4.3286	0.0027
Post - Test	1	4.3321	4.3265	0.0056
	2	4.3320	4.3264	0.0056
	3	4.3320	4.3267	0.0053
	4	4.3318	4.3264	0.0053
	5	4.3318	4.3266	0.0052
	6	4.3320	4.3213	0.0107

Top and Second Ring Radial Wear, in

Top Ring				
Cylinder	Position	Before	After	Delta
1	1	0.17390	0.17385	0.00005
	2	0.17385	0.17380	0.00005
	3	0.17350	0.17345	0.00005
	4	0.17500	0.17495	0.00005
	5	0.17675	0.17665	0.00010
2	1	0.17035	0.17030	0.00005
	2	0.17050	0.17035	0.00015
	3	0.17160	0.17140	0.00020
	4	0.17105	0.17095	0.00010
	5	0.17105	0.17100	0.00005
3	1	0.17300	0.17290	0.00010
	2	0.17290	0.17275	0.00015
	3	0.17315	0.17290	0.00025
	4	0.17405	0.17390	0.00015
	5	0.17535	0.17525	0.00010
4	1	0.17190	0.17185	0.00005
	2	0.17110	0.17105	0.00005
	3	0.17085	0.17075	0.00010
	4	0.17050	0.17030	0.00020
	5	0.17185	0.17185	0.00000
5	1	0.17115	0.17110	0.00005
	2	0.17095	0.17090	0.00005
	3	0.17195	0.17180	0.00015
	4	0.17085	0.17080	0.00005
	5	0.17135	0.17130	0.00005
6	1	0.17090	0.17085	0.00005
	2	0.17090	0.17080	0.00010
	3	0.17225	0.17220	0.00005
	4	0.17145	0.17140	0.00005
	5	0.17095	0.17090	0.00005
*Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error				

Maximum	0.00025
Average	0.00009

Second Ring				
Cylinder	Position	Before	After	Delta
1	1	0.16885	0.16845	0.00040
	2	0.16960	0.16950	0.00010
	3	0.16970	0.16960	0.00010
	4	0.16890	0.16885	0.00005
	5	0.16825	0.16815	0.00010
2	1	0.16930	0.16915	0.00015
	2	0.16865	0.16860	0.00005
	3	0.16850	0.16840	0.00010
	4	0.16840	0.16835	0.00005
	5	0.16825	0.16820	0.00005
3	1	0.16875	0.16865	0.00010
	2	0.16850	0.16850	0.00000
	3	0.16710	0.16705	0.00005
	4	0.16815	0.16810	0.00005
	5	0.16825	0.16820	0.00005
4	1	0.17075	0.17065	0.00010
	2	0.17000	0.16995	0.00005
	3	0.16875	0.16865	0.00010
	4	0.17005	0.17000	0.00005
	5	0.16960	0.16945	0.00015
5	1	0.16885	0.16875	0.00010
	2	0.16830	0.16830	0.00000
	3	0.16770	0.16760	0.00010
	4	0.16920	0.16910	0.00010
	5	0.16940	0.16935	0.00005
6	1	0.16865	0.16850	0.00015
	2	0.16755	0.16750	0.00005
	3	0.16690	0.16690	0.00000
	4	0.16795	0.16790	0.00005
	5	0.16825	0.16815	0.00010
*Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error				

Maximum	0.00040
Average	0.00009

Piston Ring Gap Measurements, in

Cylinder	Ring No.	After
1	1	0.017
	2	0.052
	3	0.024
2	1	0.017
	2	0.052
	3	0.021
3	1	0.017
	2	0.053
	3	0.018
4	1	0.017
	2	0.052
	3	0.025
5	1	0.018
	2	0.052
	3	0.018
6	1	0.018
	2	0.051
	3	0.021

Piston Ring Mass, grams

Cylinder	Ring No.	Before	After	Delta
1	1	28.8816	28.8767	0.0049
	2	27.0807	27.0756	0.0051
	3	17.0928	17.0793	0.0135
2	1	28.5399	28.5268	0.0131
	2	26.9325	26.9271	0.0054
	3	17.1378	17.1233	0.0145
3	1	28.8637	28.8565	0.0072
	2	27.0885	27.0834	0.0051
	3	16.9769	16.9665	0.0104
4	1	28.4821	28.4658	0.0163
	2	27.3046	27.2978	0.0068
	3	17.1648	17.1508	0.0140
5	1	28.3389	28.3290	0.0099
	2	27.2477	27.2409	0.0068
	3	17.0677	17.0677	0.0000
6	1	28.4008	28.3887	0.0121
	2	27.0724	27.0611	0.0113
	3	17.1153	17.1027	0.0126

Ring No. 1 max decrease	0.0163
Ring No. 2 max decrease	0.0113
Ring No. 3 max decrease	0.0145

Ring No. 1 avg decrease	0.0106
Ring No. 2 avg decrease	0.0067
Ring No. 3 avg decrease	0.0108

Connecting Rod Bearing Weight Loss, grams

Rod Bearing	Shell	Before	After	Change
1	Top	76.0968	76.0622	0.0346
	Bottom	75.8867	75.8738	0.0129
2	Top	75.9613	75.9302	0.0311
	Bottom	76.0039	75.9936	0.0103
3	Top	75.7139	75.6712	0.0427
	Bottom	75.9586	75.9502	0.0084
4	Top	75.8854	75.8518	0.0336
	Bottom	75.8033	75.7938	0.0095
5	Top	75.7739	75.7538	0.0201
	Bottom	75.4391	75.4278	0.0113
6	Top	75.7585	75.7231	0.0354
	Bottom	75.5271	75.5201	0.0070

Maximum	0.0427
Average	0.0214

Main Bearing Weight Loss, grams

Main Bearing	Shell	Before	After	Change
1	Top	73.3167	73.3097	0.0070
	Bottom	81.5411	81.5370	0.0041
2	Top	73.3194	73.3157	0.0037
	Bottom	81.4706	81.4667	0.0039
3	Top	73.3027	73.3000	0.0027
	Bottom	81.3285	81.3256	0.0029
4	Top	73.4279	73.4258	0.0021
	Bottom	80.7418	80.7386	0.0032
5	Top	73.4968	73.4934	0.0034
	Bottom	81.7373	81.7334	0.0039
6	Top	142.7524	142.7086	0.0438
	Bottom	81.3148	81.3110	0.0038
7	Top	73.3760	73.3657	0.0103
	Bottom	81.0446	81.0408	0.0038

Maximum	0.0438
Average	0.0070

Photographs

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Piston Skirt Thrust - Best Cyl. 5

Piston Skirt Anti-thrust - Best Cyl. 5

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Piston Skirt Thrust - Worst Cyl. 6

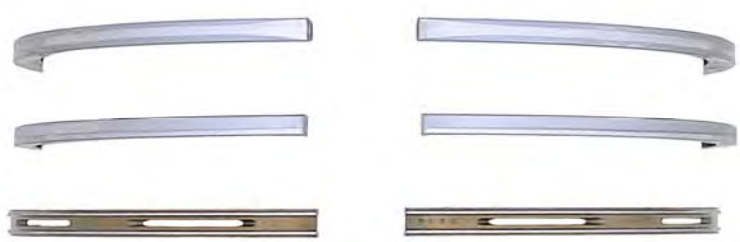
Piston Skirt Anti-thrust - Worst Cyl. 6

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Piston Rings - Best Cyl. 5

Piston Rings - Worst Cyl. 4



CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	EOT Date:	08/26/09
Test No.:	LO228213-C71-2W-420	Test Hours:	630

Piston Undercrown - Best Cyl. 5

Piston Undercrown - Worst Cyl. 6

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Engine Block Cylinder Bore - Best Cyl. 3

Engine Block Cylinder Bore - Worst Cyl. 6

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Intake and Exhaust Valve - Best Cyl. 3

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Intake and Exhaust Valve - Worst Cyl. 1

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

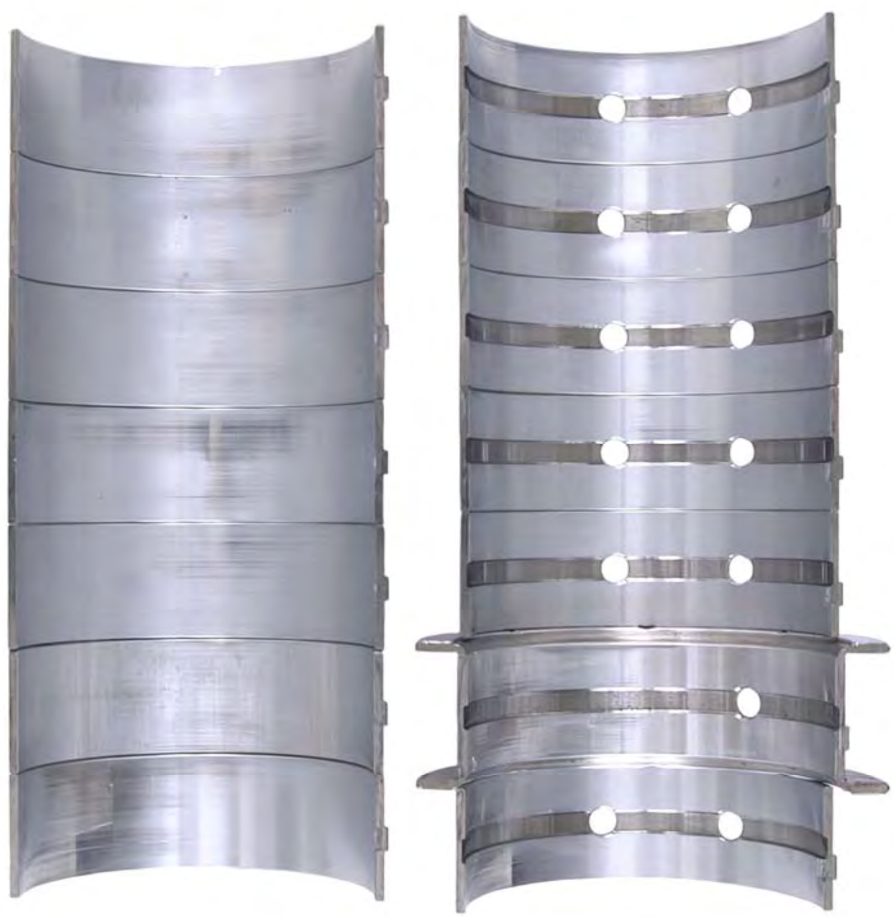
Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Rod Bearings

CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Main Bearings



CAT C7 -TACTICAL WHEELED VEHICLE CYCLE

Oil Code:	LO-228213	**EOT Date:**	08/26/09
Test No.:	LO228213-C71-2W-420	**Test Hours:**	630

Crossheads - 1,2,3,4,5,6

APPENDIX D

Caterpillar C7

Test Number: LO241026-C71-NATO-400

Test Procedure: NATO Standard Engine Laboratory Test

EVALUATION OF MIL-PRF-46167D OEA 0W-30 ARCTIC OIL

Work Directive No. 42

Caterpillar C7

Test Lubricant: LO-241026
Experimental Arctic Oil – 0W30 OEA Lubrizol
Test Fuel: JP-8
Test Number: LO241026-C71-NATO-400
Start of Test Date: October 11, 2009
End of Test Date: December 17, 2009
Test Duration: 400 Hours
Test Procedure: NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Introduction

This test was used to evaluate an experimental arctic oil, Lubrizol OEA 0W30, for use in military tactical vehicles using the procedures outlined in the NATO Standard Engine Laboratory Test (AEP-5 Edition 3). This work was completed in support of Work Directive 42, Single Common Powertrain Lubricants for Combat/Tactical Equipment.

Test Engine

The experimental oil was evaluated in a Caterpillar C7 turbocharged diesel engine, representative of engines currently used in military equipment, including a variety of FMTVs. Prior to testing the engine was disassembled and measured for pre-test wear. Engine clearances and specifications were measured, and the engine was reassembled following standard assembly procedures.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for Caterpillar C7 testing. Engine monitoring, control, and data acquisition were supplied by Southwest Research Institute (SwRI) developed PRISM software. A 500-hp absorbing dynamometer was used for engine loading. Engine oil, fuel, and coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers. Engine intake air was supplied at ambient conditions.

Engine Run-in

Prior to testing, the engine was run-in using the candidate oil following the procedure outlined below. The engine was started and given one minute at idle to check for fluid leaks. Following this, 10 operating points were used to represent the operating range of the engine. This was repeated for 6 cycles, giving an engine run-in time of approximately five and a half hours.

Step	Time, min	Speed, RPM	Torque, ft-lbs	Coolant Out, Deg F	Fuel Temp, Deg F
1	1	750	0	190	90
2	10	1400	187	190	90
3	10	1900	175	190	90
4	10	2400	175	190	90
5	5	2400	320	190	90
6	5	1900	350	190	90
7	5	1400	375	190	90
8	3	1400	100%	190	90
9	3	1900	100%	190	90
10	3	2400	100%	190	90

Figure 1 - Test Engine Run-In Procedure

Pre-Test Engine Performance Check

After completion of engine run-in, a full load powercurve was performed at points from 1000 rpm to near governed engine speed (~2788 rpm) for determination of pre-test engine performance. This initial engine performance check was completed using the same oil charge used during the engine run-in segment. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during oil evaluation was the standard 400 hr NATO cycle as outlined in AEP-5 Edition 3, Part II. The test cycle consists of 10 steps running for a total of 10 hours. This cycle is repeated 40 times total at a rate of two cycles per day. Total daily run-time was 20 hrs with a 4 hour soak before resuming testing. This allows for less total days of testing. As outlined in the testing procedure, the engine was allowed to soak for at least eight hours once every 100 test hours (Section 2.4.7). Step 5 of the cycle alternates between idle for four minutes and rated conditions for six minutes, repeating in a loop twelve times to complete the two hour step. Engine oil, coolant, and fuel temperatures were elevated to simulate conditions consistent with desert climate use. Engine operating parameters were controlled throughout testing as specified in the table below.

Step	Speed, RPM	Load, %	Duration, hrs	Oil Temp, Deg F	Coolant Temp, Deg F	Fuel Temp, deg F
1	Idle	0	0.5	260	223.5	100
2	2400	100	2	260	223.5	100
3	2800	0	0.5	260	223.5	100
4	1800	100	1	260	223.5	100
5	Idle to 2400	0 to 100	2	260	223.5	100
6	1440	100	0.5	260	223.5	100
7	Idle	0	0.5	260	223.5	100
8	2736	70	0.5	260	223.5	100
9	1440	100	2	260	223.5	100
10	1440	50	0.5	260	223.5	100

Figure 2 - Test Cycle Operating Parameters

Engine coolant was a 60/40 blend of ethylene glycol antifreeze and deionized water. Test fuel was JP-8.

Oil Sampling

Approximately eight ounces of engine oil were sampled every 20 hours for used oil analysis. All oil samples were weighed and logged to take into account during calculations of total engine oil consumption for the test duration. Engine oil analysis consisted of the following tests.

Every 20 Hours		
ASTM	**D4739**	Total Base Number
ASTM	**D664**	Total Acid Number
ASTM	**D445**	Kinematic Viscosity @ 100° C
ASTM	**API Gravity**	API Gravity
ASTM	**D4052**	Density
ASTM	**TGA Soot**	TGA Soot
ASTM	**E168**	Oxidation
ASTM	**E168**	Nitration
ASTM	**D5185**	Wear Metals by ICP

Figure 3 - Used Oil Analysis Procedures

Used oil analysis results can be seen in the Engine Oil Analysis and Engine Oil Analysis Trends section of the report.

Oil Level Checks

Engine oil level was checked daily and replenished as needed to restore level to the dipstick "Full" mark. This process occurred before the engine was started for each 20 hour segment. All oil additions were weighed and taken into account during calculation of total engine oil consumption for the test.

Oil Change Intervals

After every 100 hours of testing the oil was eligible for change as dictated by the NATO cycle instructions. Oil analysis results at 100, 200, and 300 hours of testing allowed for the continued use of the original oil charge through the entire 400 hour test. At the completion of the test, the used oil and filter were weighed, as removed, to track oil consumption.

Mid- and Post-Test Engine Performance Check

After completion of each 100 hours of testing a full load powercurve was completed from 1000 rpm to near governed engine speed (~2788 rpm) to determine engine performance. Powercurve plots can be seen in the Engine Performance Curves section.

Engine Operating Conditions Summary

Below is a summary of the engine operating conditions over the duration of the 400 engine hours. Please note that, for consistency, the data excludes the ramps into the summarized modes.

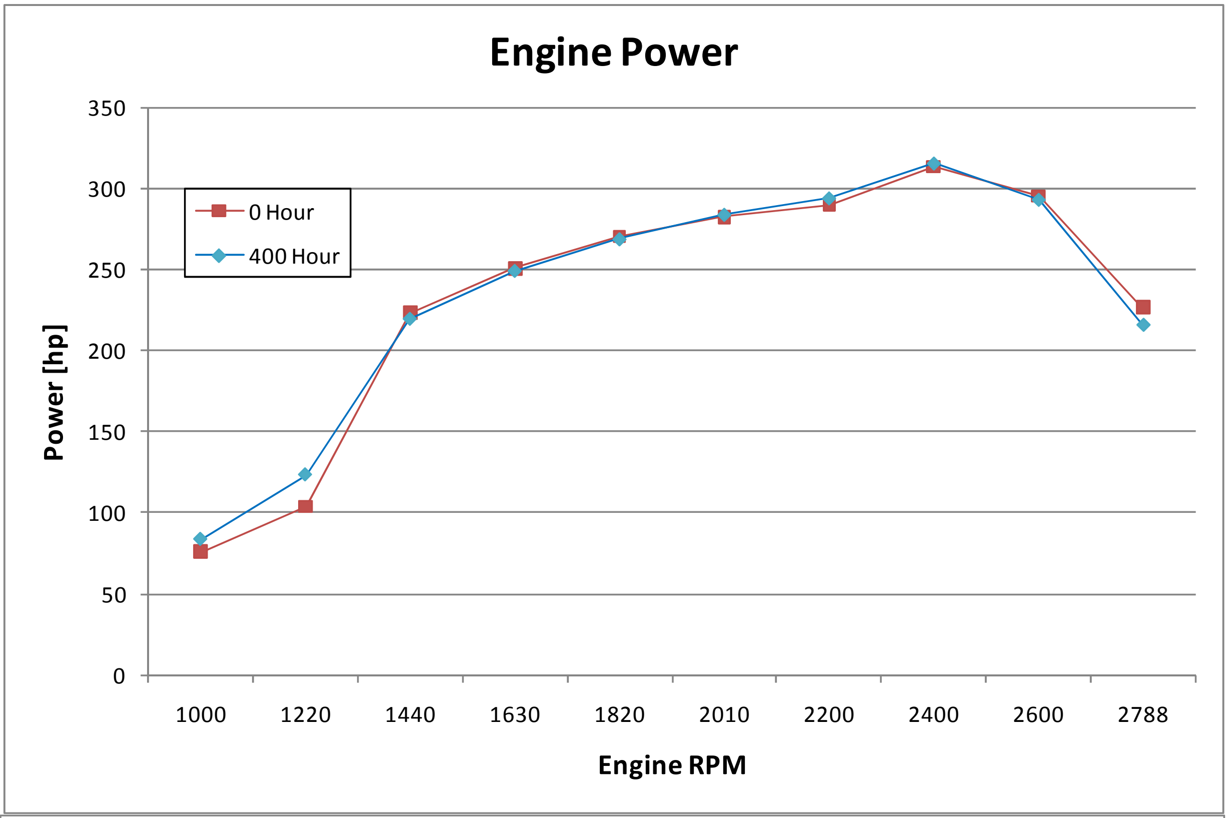
	0 to 100 Hours, NATO Mode 2					100 to 200 Hours, NATO Mode 2			
Performance	**Mean**	**Std. Dev**	**Min**	**Max**		**Mean**	**Std. Dev**	**Min**	**Max**
Engine Speed [RPM]	2399.99	0.60	2398.00	2402.00		2400.03	2.43	2387.00	2411.00
Power [hp]	311.99	2.17	305.70	320.80		318.85	3.21	305.20	327.80
Torque [ft-lb]	682.74	4.73	669.00	702.00		697.72	7.00	671.00	716.00
Fuel Consumption [lb/hr]	111.90	0.72	110.00	114.17		114.88	0.85	112.25	117.76
BSFC [lb/hp-hr]	0.36	0.00	0.35	0.37		0.36	0.00	0.35	0.37
Temperatures [Deg F]									
Oil Sump	257.79	2.28	234.30	260.20		257.39	3.08	197.70	258.90
Coolant In	211.69	0.72	209.90	221.40		211.44	0.81	207.40	221.40
Coolant Out	223.53	0.54	222.10	229.90		223.53	0.59	212.40	230.00
Fuel Inlet	99.11	3.89	77.90	106.30		94.32	3.48	73.10	100.00
Intake Air	89.64	6.83	69.30	101.60		89.58	4.69	71.60	98.40
Intake Manifold Air	114.27	8.54	92.00	130.30		120.08	10.30	92.70	136.20
Cylinder 1 Exhaust	982.61	14.02	929.10	1007.20		1018.54	8.79	963.40	1031.10
Cylinder 2 Exhaust	1125.38	8.58	1070.90	1142.10		1155.03	11.08	1079.10	1173.90
Cylinder 3 Exhaust	1107.36	13.18	1037.10	1134.10		1146.97	11.62	1063.30	1170.40
Cylinder 4 Exhaust	1060.28	9.09	1001.60	1081.30		1094.79	11.95	1011.70	1115.60
Cylinder 5 Exhaust	1082.36	10.88	1026.60	1113.10		1125.31	11.67	1051.10	1146.80
Cylinder 6 Exhaust	1017.60	6.46	983.70	1033.00		1039.52	11.05	977.70	1059.90
Exhaust Before Turbo, Rear	1132.70	9.37	1067.20	1152.90		1169.62	13.37	1080.10	1192.50
Exhaust Before Turbo, Front	1176.95	11.66	1098.40	1203.80		1207.79	11.85	1111.80	1228.00
Exhaust After Turbo	895.89	12.14	768.60	914.30		965.75	96.94	780.20	1644.50
Pressures									
Oil [psig]	42.06	0.94	40.90	47.60		41.11	0.58	40.40	52.20
Barometer [psia]	14.25	0.08	14.10	14.40		14.28	0.09	14.10	14.40
Intake, Before Compressor [psia]	13.54	0.06	13.42	13.63		13.55	0.07	13.41	13.69
Intake, After Compressor [psia]	42.82	0.12	42.50	43.10		42.85	0.12	42.60	43.20
Boost [psi]	27.29	0.09	27.00	27.60		27.28	0.08	27.00	27.50
Exhaust, After Turbo [psig]	0.50	0.02	0.28	0.57		0.42	0.10	0.15	0.58

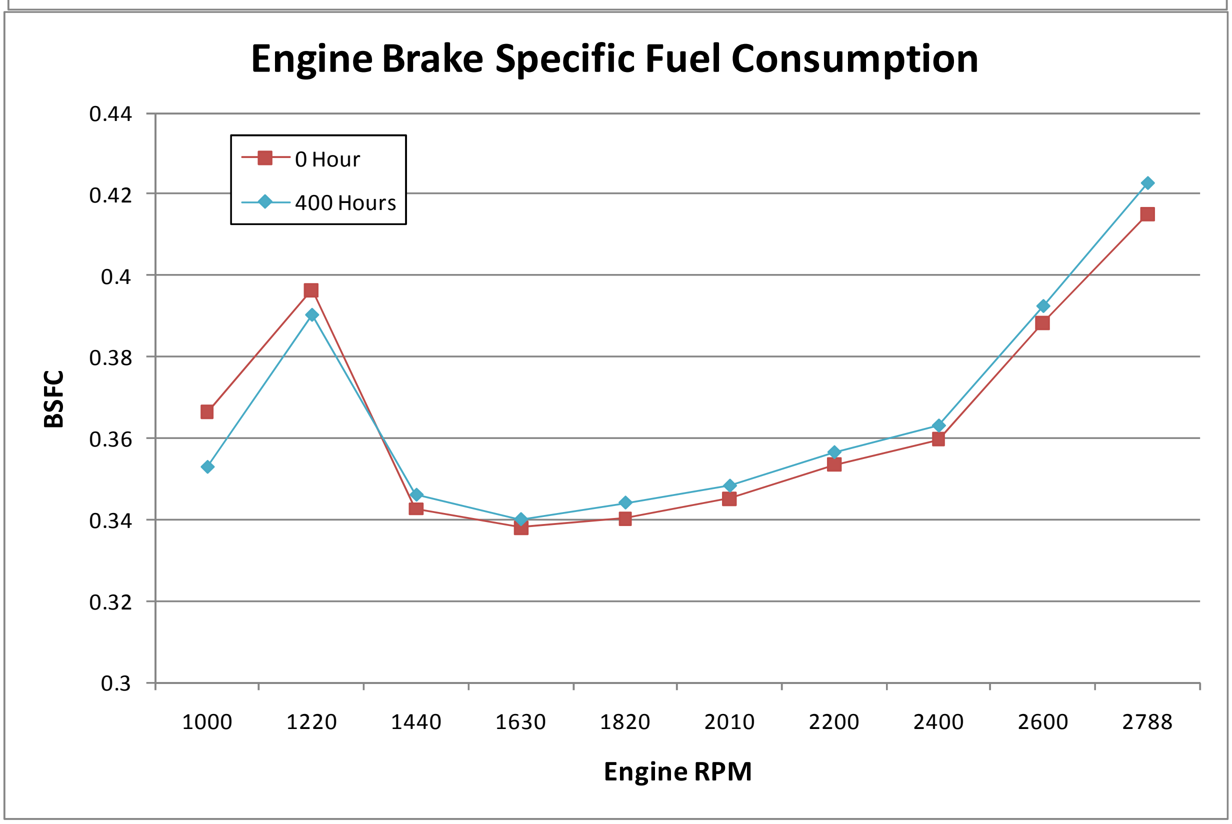
	200 to 300 Hours, NATO Mode 2					300 to 400 Hours, NATO Mode 2			
Performance	**Mean**	**Std. Dev**	**Min**	**Max**		**Mean**	**Std. Dev**	**Min**	**Max**
Engine Speed [RPM]	2400.03	1.80	2392.00	2433.00		2400.05	1.06	2393.00	2404.00
Power [hp]	316.99	5.27	123.90	353.20		312.98	3.15	306.10	324.50
Torque [ft-lb]	693.67	11.60	266.00	774.00		684.88	6.84	670.00	710.00
Fuel Consumption [lb/hr]	114.59	2.92	19.85	124.56		113.51	1.57	67.51	156.14
BSFC [lb/hp-hr]	0.36	0.01	0.06	0.38		0.36	0.00	0.22	0.49
Temperatures [Deg F]									
Oil Sump	257.34	3.04	217.90	258.90		256.17	3.23	216.20	258.10
Coolant In	211.74	0.84	209.90	221.50		211.86	0.89	205.20	222.80
Coolant Out	223.55	0.53	222.10	229.90		223.54	0.59	210.60	230.20
Fuel Inlet	93.38	5.96	66.30	100.80		97.05	5.57	73.50	101.40
Intake Air	84.56	8.89	63.20	110.20		89.10	6.72	65.40	102.20
Intake Manifold Air	122.72	8.17	88.60	137.10		123.14	8.11	90.30	137.90
Cylinder 1 Exhaust	1007.24	10.06	965.20	1196.90		1001.79	13.67	955.50	1034.30
Cylinder 2 Exhaust	1138.84	13.35	1080.60	1234.60		1126.43	10.72	1060.00	1154.70
Cylinder 3 Exhaust	1144.72	12.70	907.00	1173.60		1144.13	10.12	1067.00	1171.00
Cylinder 4 Exhaust	1091.05	18.36	362.90	1120.40		1089.60	10.53	1025.10	1118.50
Cylinder 5 Exhaust	1138.90	25.33	423.10	1181.20		1154.12	12.32	1077.80	1181.00
Cylinder 6 Exhaust	1041.59	16.61	435.30	1071.00		1033.89	11.74	978.50	1060.90
Exhaust Before Turbo, Rear	1176.53	21.00	414.90	1210.00		1179.77	12.04	1100.30	1209.40
Exhaust Before Turbo, Front	1198.06	13.71	1118.10	1232.20		1192.23	11.43	1102.00	1220.70
Exhaust After Turbo	1540.00	217.72	757.00	1644.50		1616.66	137.07	773.20	1644.50
Pressures									
Oil [psig]	40.14	0.80	38.40	46.80		39.21	0.51	38.60	46.00
Barometer [psia]	14.34	0.09	14.10	14.50		14.36	0.11	14.10	14.60
Intake, Before Compressor [psia]	13.55	0.07	13.36	13.84		13.52	0.08	13.32	13.66
Intake, After Compressor [psia]	42.97	0.27	30.60	43.30		43.01	0.16	42.50	43.40
Boost [psi]	27.28	0.24	16.20	27.60		27.30	0.10	27.00	27.60
Exhaust, After Turbo [psig]	0.61	0.14	0.24	1.01		0.54	0.03	0.35	0.63

	0 to 100 Hours, NATO Mode 9					100 to 200 Hours, NATO Mode 9			
Performance	**Mean**	**Std. Dev**	**Min**	**Max**		**Mean**	**Std. Dev**	**Min**	**Max**
Engine Speed [RPM]	1439.97	1.14	1419.00	1443.00		1439.95	2.68	1389.00	1494.00
Power [hp]	215.97	1.76	210.40	221.50		212.37	8.90	171.10	230.90
Torque [ft-lb]	787.68	6.40	767.00	808.00		774.55	32.50	608.00	843.00
Fuel Consumption [lb/hr]	73.97	0.53	72.97	76.25		73.40	2.34	66.35	75.30
BSFC [lb/hp-hr]	0.34	0.00	0.34	0.35		0.35	0.00	0.32	0.41
Temperatures [Deg F]									
Oil Sump	246.86	1.09	245.50	255.00		246.23	1.07	236.10	253.60
Coolant In	210.37	0.59	208.30	212.20		210.39	0.70	208.40	215.00
Coolant Out	223.50	0.51	222.00	225.40		223.50	0.56	222.10	226.00
Fuel Inlet	91.90	3.10	84.00	102.80		89.39	2.10	84.40	101.10
Intake Air	91.88	4.41	78.50	99.80		90.67	3.24	82.20	100.10
Intake Manifold Air	103.76	5.18	96.20	112.90		106.22	5.65	95.40	116.50
Cylinder 1 Exhaust	987.37	4.10	971.80	997.80		995.68	8.16	969.10	1023.00
Cylinder 2 Exhaust	1157.98	6.11	1143.60	1179.00		1167.46	7.53	1146.70	1196.80
Cylinder 3 Exhaust	1133.82	6.80	1115.80	1150.50		1150.06	8.75	1124.80	1180.50
Cylinder 4 Exhaust	1086.55	4.83	1072.40	1105.80		1099.49	8.62	1069.30	1121.90
Cylinder 5 Exhaust	1137.12	6.17	1114.60	1149.10		1147.30	9.57	1115.00	1170.40
Cylinder 6 Exhaust	1059.79	3.75	1048.10	1072.20		1062.88	11.76	1023.90	1084.20
Exhaust Before Turbo, Rear	1197.39	5.49	1177.50	1210.20		1207.29	8.62	1179.40	1233.10
Exhaust Before Turbo, Front	1216.00	6.19	1197.70	1284.00		1227.88	7.51	1204.00	1256.30
Exhaust After Turbo	1022.16	5.50	988.40	1034.60		1232.37	278.13	991.60	1644.50
Pressures									
Oil [psig]	32.26	0.83	30.60	34.40		30.97	0.32	28.90	31.70
Barometer [psia]	14.25	0.08	14.10	14.40		14.24	0.08	14.10	14.40
Intake, Before Compressor [psia]	14.02	0.06	13.93	14.16		14.00	0.07	13.88	14.14
Intake, After Compressor [psia]	37.36	0.43	36.30	38.40		37.20	0.77	33.80	38.20
Boost [psi]	22.65	0.35	21.70	23.60		22.51	0.77	19.70	23.60
Exhaust, After Turbo [psig]	0.06	0.01	0.03	0.08		0.05	0.01	-0.01	0.08

	200 to 300 Hours, NATO Mode 9					300 to 400 Hours, NATO Mode 9			
Performance	**Mean**	**Std. Dev**	**Min**	**Max**		**Mean**	**Std. Dev**	**Min**	**Max**
Engine Speed [RPM]	1440.04	1.95	1388.00	1490.00		1439.97	1.30	1428.00	1449.00
Power [hp]	211.72	7.52	170.90	220.70		205.07	8.66	192.00	219.70
Torque [ft-lb]	772.16	27.36	644.00	804.00		747.95	31.52	701.00	800.00
Fuel Consumption [lb/hr]	74.01	1.48	70.70	76.94		72.43	1.73	70.09	76.02
BSFC [lb/hp-hr]	0.35	0.01	0.33	0.42		0.35	0.01	0.33	0.38
Temperatures [Deg F]									
Oil Sump	246.75	0.74	245.30	252.70		245.46	0.93	243.60	251.80
Coolant In	210.41	0.68	207.20	212.00		210.61	1.21	206.90	215.60
Coolant Out	223.50	0.58	221.90	224.80		223.51	0.75	221.30	226.10
Fuel Inlet	86.80	5.56	79.20	100.00		94.27	5.91	76.20	100.90
Intake Air	83.89	6.16	72.60	93.20		86.66	5.83	74.50	96.40
Intake Manifold Air	103.28	3.04	95.50	109.30		100.50	4.40	93.30	113.80
Cylinder 1 Exhaust	1003.15	27.66	973.70	1061.20		1022.82	39.49	956.70	1089.60
Cylinder 2 Exhaust	1170.33	18.54	1141.50	1211.50		1167.30	16.95	1123.50	1203.30
Cylinder 3 Exhaust	1152.67	21.27	1122.60	1198.50		1149.69	19.76	1109.10	1191.20
Cylinder 4 Exhaust	1108.76	15.54	1086.30	1144.20		1113.00	16.55	1078.30	1150.40
Cylinder 5 Exhaust	1165.02	18.27	1140.10	1215.50		1179.16	19.54	1142.60	1221.60
Cylinder 6 Exhaust	1070.06	15.68	1042.60	1099.20		1071.09	15.14	1039.60	1105.00
Exhaust Before Turbo, Rear	1223.31	20.93	1195.80	1273.90		1233.96	23.79	1196.40	1284.00
Exhaust Before Turbo, Front	1232.57	26.39	1192.20	1288.50		1236.52	27.04	1192.30	1290.10
Exhaust After Turbo	1633.38	70.69	1019.80	1644.50		1644.02	11.90	1201.60	1644.50
Pressures									
Oil [psig]	29.29	0.80	26.80	30.70		28.21	0.44	27.00	29.20
Barometer [psia]	14.36	0.11	14.20	14.50		14.37	0.07	14.20	14.50
Intake, Before Compressor [psia]	14.06	0.08	13.89	14.21		14.05	0.08	13.87	14.14
Intake, After Compressor [psia]	37.15	1.30	34.60	38.70		36.06	1.29	34.30	38.20
Boost [psi]	22.31	1.20	19.70	23.60		21.22	1.27	19.60	23.30
Exhaust, After Turbo [psig]	0.11	0.06	0.03	0.26		0.08	0.02	0.02	0.12

Engine Performance Curves

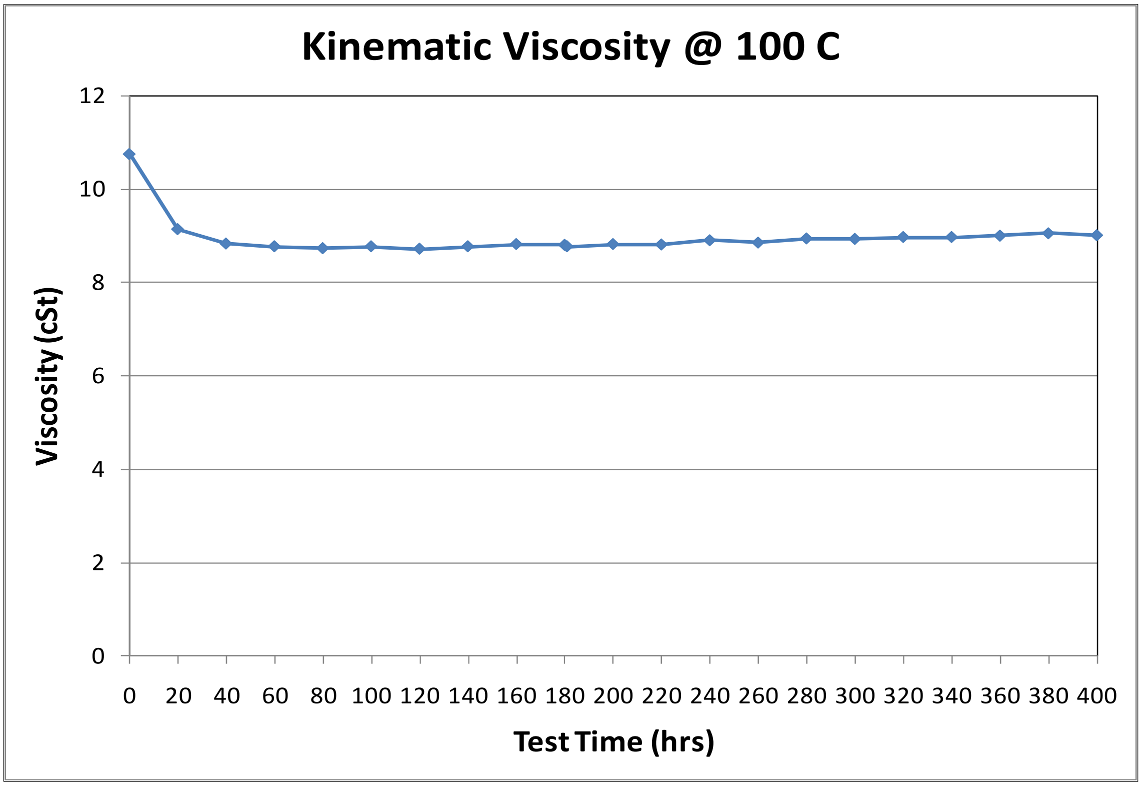


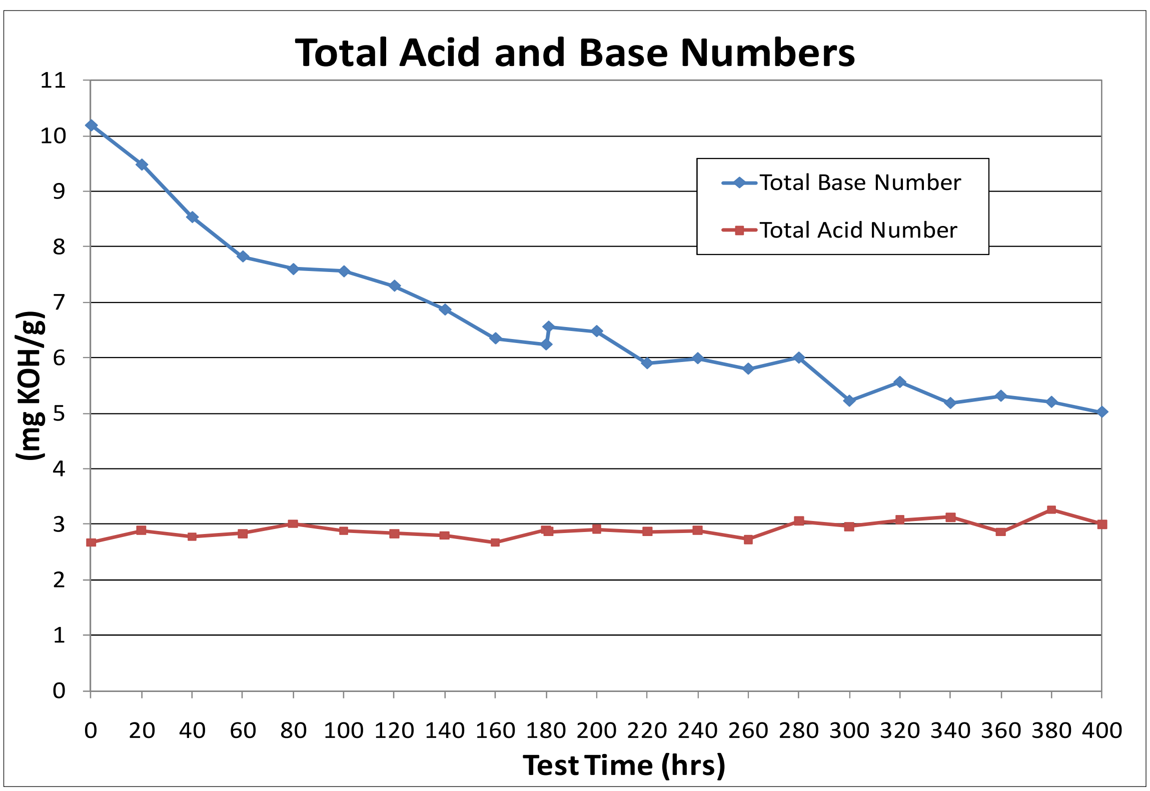


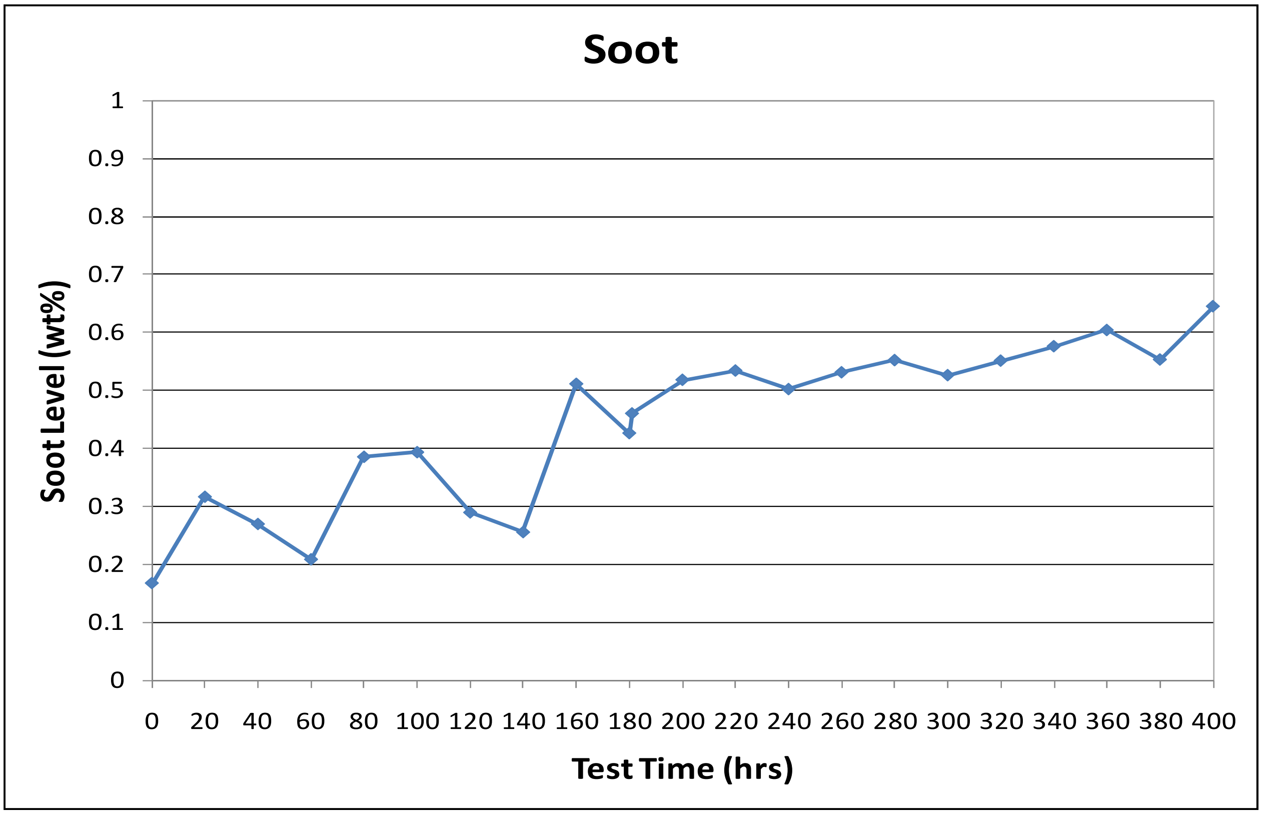
Engine Oil Analysis

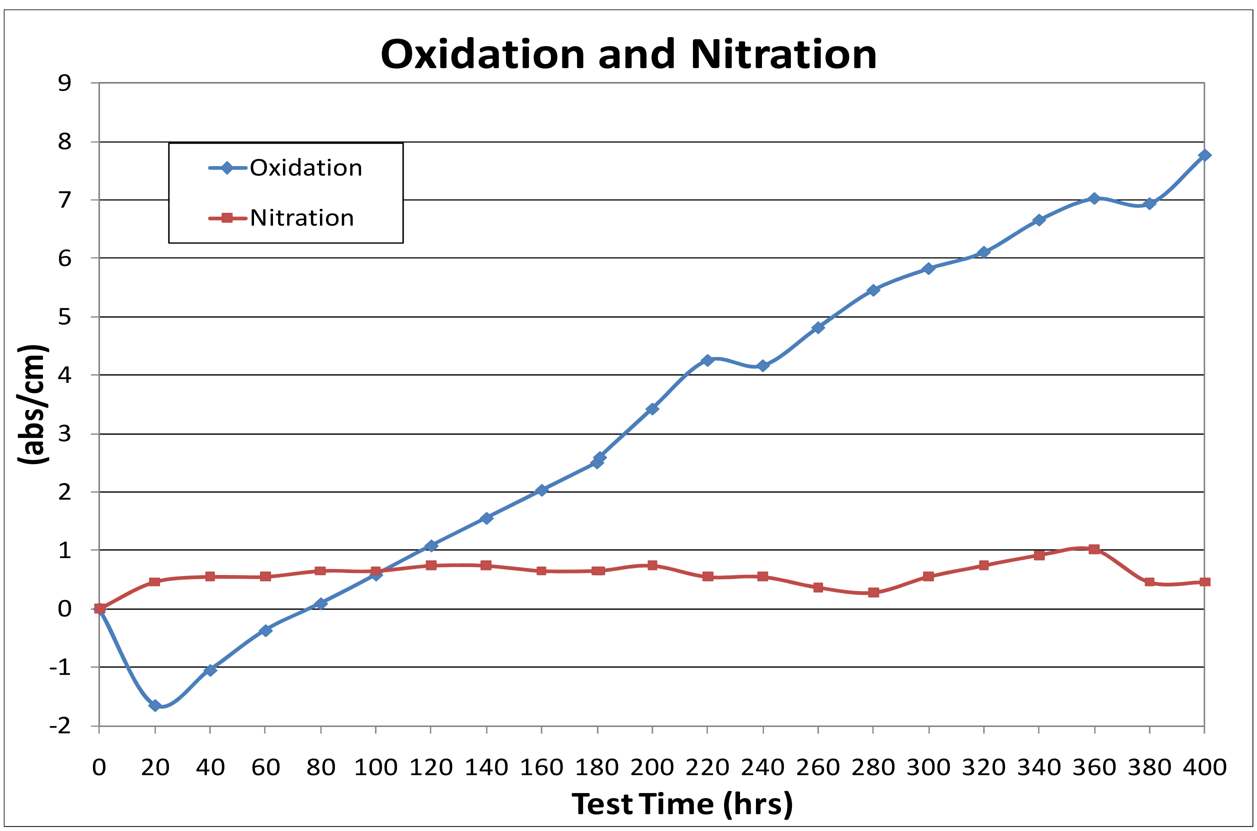
Property	ASTM Test Number	Test Hours																				
		0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
Total Base Numer [mg KOH/g]	D4739	10.2	9.49	8.54	7.83	7.6	7.56	7.3	6.87	6.35	6.24	6.48	5.9	5.99	5.8	6	5.22	5.56	5.18	5.31	5.2	5.02
Total Acid Numer [mg KOH/g]	D664	2.67	2.89	2.78	2.83	3.01	2.88	2.83	2.8	2.67	2.9	2.91	2.87	2.89	2.73	3.06	2.96	3.08	3.13	2.86	3.26	3
Viscosity @ 100 C [cst]	D445	10.76	9.14	8.83	8.77	8.73	8.77	8.72	8.77	8.82	8.8	8.82	8.81	8.9	8.85	8.94	8.93	8.97	8.97	9	9.05	9.01
Density [g/ml]	D4052	0.8493	0.8496	0.8499	0.8502	0.8504	0.8506	0.8508	0.851	0.8513	0.8515	0.8518	0.852	0.852	0.8525	0.8527	0.8528	0.8529	0.8531	0.8532	0.8533	0.8537
Soot (TGA)	Soot	0.167	0.316	0.269	0.208	0.385	0.393	0.289	0.255	0.511	0.426	0.518	0.534	0.502	0.531	0.552	0.526	0.551	0.576	0.604	0.553	0.645
Oxidation [Abs/cm]	E168 FTNG	0	-1.65	-1.05	-0.37	0.09	0.58	1.08	1.55	2.03	2.5	3.42	4.25	4.16	4.81	5.45	5.82	6.1	6.65	7.02	6.93	7.76
Nitration [Abs/cm]		0	0.46	0.55	0.55	0.65	0.65	0.74	0.74	0.65	0.65	0.74	0.55	0.55	0.37	0.28	0.55	0.74	0.92	1.02	0.46	0.46
Wear Metals by ICP [ppm]	D5185																					
Al		1	3	5	9	10	11	12	12	13	13	14	17	19	22	24	25	22	22	22	20	22
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		2	2	<1	<1	2	2	<1	<1	<1	2	1	1	2	1	<1	<1	1	1	<1	<1	3
Ca		3476	3575	3660	3610	3677	3640	3660	3683	3712	3763	3768	3675	3775	3901	3798	3760	3914	3826	3905	3853	3895
Cr		<1	<1	2	2	3	3	3	3	4	4	4	4	4	5	4	5	5	5	5	5	5
Cu		<1	6	10	14	15	16	16	16	17	18	21	69	219	345	327	320	344	301	284	266	230
Fe		2	80	130	162	163	165	171	166	169	169	176	173	171	170	161	160	156	157	159	154	156
Pb		<1	<1	2	3	2	2	2	2	3	2	2	2	3	2	2	2	2	3	3	2	3
Mg		10	9	10	10	11	10	12	12	11	12	11	11	11	12	11	12	12	12	13	12	12
Mn		<1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mo		1	1	1	<1	1	1	1	1	1	1	1	1	1	2	2	2	2	1	2	1	2
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1313	1275	1280	1177	1175	1133	1142	1126	1120	1114	1110	1084	1118	1130	1104	1106	1158	1111	1107	1116	1120
Si		5	4	7	8	8	9	8	8	10	10	12	14	12	14	10	12	12	13	13	15	13
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	5	<5	6	<5	5	6	5	<5	<5	<5	<5	<5	5	5	<5	<5	5	7	5	<5
Sn		<1	<1	1	2	2	2	2	2	2	2	3	3	3	3	3	4	3	4	3	4	3
Zn		1490	1474	1383	1431	1429	1413	1410	1395	1425	1431	1437	1434	1457	1435	1389	1386	1430	1404	1416	1425	1435
K		6	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr		<1	<1	1	1	1	<1	1	1	<1	<1	<1	<1	1	1	<1	1	<1	1	<1	1	1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

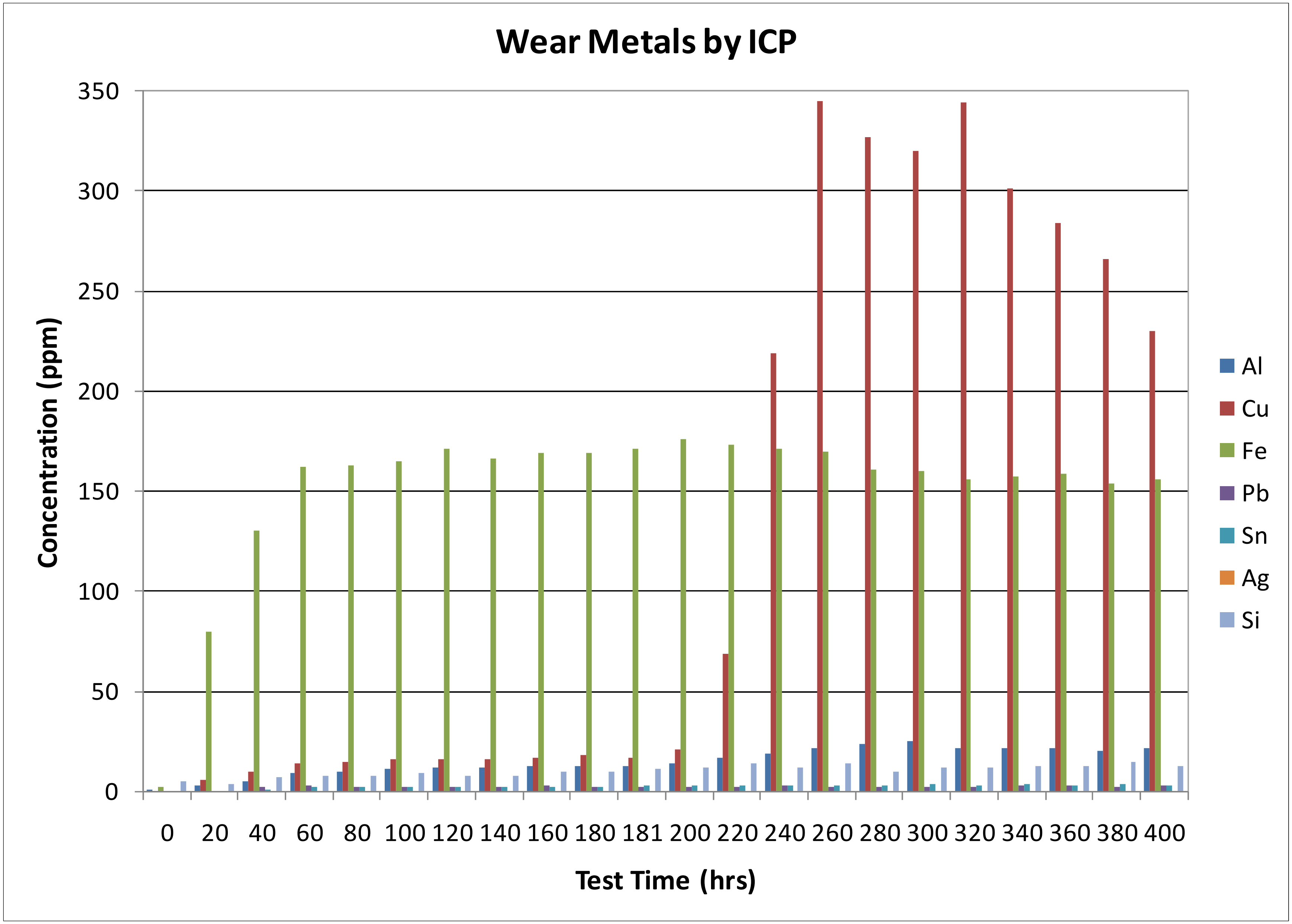
Engine Oil Analysis Trends






Soot
Soot Level (wt%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Test Time (hrs)


Oxidation and Nitration
Oxidation
Nitration
(abs/cm)
9
8
7
6
5
4
3
2
1
0
-1
-2
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Test Time (hrs)


Wear Metals by ICP
Concentration (ppm)
350
300
250
200
150
100
50
0
0 20 40 60 80 100 120 140 160 180 181 200 220 240 260 280 300 320 340 360 380 400
Test Time (hrs)
Al
Cu
Fe
Pb
Sn
Ag
Si

Oil Consumption Data

Average oil consumption per test hour was 0.071 lbs/hr.

Hour	Additions (lbs)	Samples (lbs)	Consumption (lbs)	Cosumption Accumulated
20	0	0.42	*0*	*0*
40	0.51	0.5	0.01	0.01
60	2.36	0.49	1.87	1.88
80	2.1	0.5	1.6	3.48
100	1.94	0.44	1.5	4.98
120	2.21	0.45	1.76	6.74
140	0.79	0.46	0.33	7.07
160	1.26	0.48	0.78	7.85
180	1.36	0.43	0.93	8.78
181	0	0.28	-0.28	8.5
200	1.37	0.39	0.98	9.48
220	2.94	0.47	2.47	11.95
240	1.53	0.47	1.06	13.01
260	1.05	0.48	0.57	13.58
280	2.3	0.46	1.84	15.42
300	2.78	0.49	2.29	17.71
320	0.9	0.46	0.44	18.15
340	1.52	0.48	1.04	19.19
360	1.6	0.41	1.19	20.38
380	1.95	0.54	1.41	21.79
400	0	0.17	-0.17	21.62
	Initial Fill	36.5	**Total Additions**	30.47
	EOT Drain	28.3	**Total Samples**	9.27
	Dry Filter	2.13	**Wet Filter**	3.14
		(Initial Fill + Additions+Dry Filter)	69.1	
		(EOT Drain + Samples+Wet Filter)	40.71	
		Total Oil Consumption	28.39	

List of Engine Shutdowns and Corrective Actions

The engine itself did not have any mechanical failures, however there were several issues related to peripheral equipment requiring the test stand to shut down. After each shutdown, the engine was restarted at the beginning of the mode in which the failure occurred, according to the NATO test procedure.

Test Time	Shutdown Failure	Corrective Action
180 hrs	Low Oil Gally Pressure	None, occurred while sampling
181 hrs	Dyno Bearing Failure	Repair of Dynamometer
182 hrs	Low Dyno Oiler Pressure	Changed fluid after Dyno Install
199 hrs	Controller Speed Limit	Adjusted Step 9 Controller
206 hrs	Controller Speed Limit	Adjusted Step 5 Controller
209 hrs	Controller Speed Limit	Adjusted Step 5 Controller
224 hrs	Low Dyno Oiler Pressure	Repair of Pressure Switch
247 hrs	Loss of Fuel Pressure	Restarted Facility Fuel Pump
374 hrs	High Temperature Estop	Replaced Faulty Thermocouple

Post Test Engine Ratings

Ratings	Clyinder Number						
	1	2	3	4	5	6	Avg
Ring Sticking							
Ring No.1	No	No	No	No	No	No	--
Ring No.2	No	No	No	No	No	No	--
Ring No.3	No	No	No	No	No	No	--
Scuffing % Area							
Ring No.1	0	0	0	0	0	0	0.00
Ring No.2	0	0	0	0	0	0	0.00
Ring No.3	0	0	0	0	0	0	0.00
Piston Crown	0	0	0	0	0	0	0.00
Piston Skirt	0	0	0	0	0	0	0.00
Cylinder Liner, %	0	0	0	0	0	0	0.00
Piston Carbon, Demerits							
No.1 Groove	42.50	40.50	59.25	58.25	33.00	66.00	49.92
No.2 Groove	4.50	7.25	7.25	4.25	2.75	5.00	5.17
No.3 Groove	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No.1 Land	46.00	34.75	37.75	28.75	35.00	31.00	35.54
No.2 Land	41.50	30.00	44.75	44.75	44.25	38.25	40.58
No.3 Land	0.00	0.00	0.00	0.00	1.50	0.00	0.25
No.4 Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Piston Lacquer, Demerits							
No.1 Groove	0.00	0.00	0.00	0.00	0.00	0.00	0.00
No.2 Groove	2.23	2.25	1.95	2.81	3.75	2.42	2.57
No.3 Groove	2.78	2.56	2.34	2.48	2.44	1.64	2.37
No.1 Land	0.00	0.00	0.00	0.00	0.10	0.00	0.02
No.2 Land	0.31	0.68	0.38	0.24	0.19	0.64	0.41
No.3 Land	2.57	2.67	2.31	2.20	2.15	2.87	2.46
No.4 Land	1.20	1.76	1.20	1.90	1.30	1.62	1.50
Under Crown	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Total, Demerits	145.09	123.92	158.68	147.13	127.93	150.94	142.28
Miscellanous							
Top Groove Fill, %	40	57	50	54	28	58	47.83
Intermediate Groove Fill, %	0	1	1	0	0	1	0.50
Top Land Heavy Carbon, %	28	13	17	5	14	8	14.17
Top Land Flaked Carbon, %	0	0	0	0	0	0	0.00
Valve Tulip Deposits, Merits							
Exahust	9.0	9.0	9.0	9.0	9.0	9.0	9.00
Intake, Front	9.6	9.7	9.7	9.7	9.6	9.6	9.65
Intake, Rear	9.7	9.4	9.6	9.6	9.6	9.3	9.53
Intake, Average	9.7	9.6	9.7	9.7	9.6	9.5	9.59

Engine Measurement Changes

Engine Rebuild Measurements, inches

Cylinder Bore	Minimum	Maximum	Average	Spec:
Inside Diameter	4.3317	4.3323	4.3319	4.3307"-4.3327"
Out of Round	0.0003	0.0023	0.0012	Maximum 0.0010"
Taper	0.0003	0.0015	0.0009	
Piston Skirt Diameter	4.3272	4.3278	4.3276	
Piston Skirt to Cylinder Bore Clearance	0.0038	0.0048	0.0043	0.0020"-0.0050"
Piston Ring End Gaps				
Top Ring	0.018	0.018	0.018	
Second Ring	0.052	0.055	0.053	
Oil Control Ring	0.018	0.018	0.018	
Ring To Groove Clearance				
Second Ring	0.002	0.002	0.002	
Oil Control Ring	0.002	0.0025	0.002417	
Piston Pin				
Piston Pin Diameter	1.5740	1.5745	1.5741	1.5743"-1.5747"
Piston Bore Diameter	1.5750	1.5760	1.5752	1.5757"-1.5763"
Piston Pin Clearance	0.0010	0.0015	0.0011	0.0010"-0.0040"
Bearing Clerances				
Connecting Rod to Journal	0.0035	0.0045	0.00375	0.0021"-0.0061"
Main Bearing to Journal	0.004	0.004	0.004	0.0028"-0.0068"

Pre-Test Cylinder Bore Measurements, inches

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.3309	4.3323		0.0014
	Middle	4.3318	4.3327	4.3320	0.0009
	Bottom	4.3322	4.3325		0.0003
	Taper	0.0013	0.0004		
2	Top	4.3308	4.3328		0.0020
	Middle	4.3314	4.3332	4.3318	0.0018
	Bottom	4.3321	4.3327		0.0006
	Taper	0.0013	0.0005		
3	Top	4.3308	4.3329		0.0021
	Middle	4.3315	4.3333	4.3319	0.0018
	Bottom	4.3322	4.3327		0.0005
	Taper	0.0014	0.0006		
4	Top	4.3309	4.3328		0.0019
	Middle	4.3313	4.3331	4.3317	0.0018
	Bottom	4.3320	4.3326		0.0006
	Taper	0.0011	0.0005		
5	Top	4.3307	4.3330		0.0023
	Middle	4.3313	4.3332	4.3318	0.0019
	Bottom	4.3322	4.3326		0.0004
	Taper	0.0015	0.0006		
6	Top	4.3312	4.3322		0.0010
	Middle	4.3319	4.3325	4.3323	0.0006
	Bottom	4.3326	4.3322		0.0004
	Taper	0.0014	0.0003		

Post-Test Cylinder Bore Measurements, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. (ABD), (TD@MID + TD@BOT)/2	Out of Round
1	Top	4.3328	4.3322		0.0006
	Middle	4.3322	4.3318	4.3320	0.0004
	Bottom	4.3318	4.3318		0.0000
	Taper	0.0010	0.0004		
2	Top	4.3330	4.3318		0.0012
	Middle	4.3327	4.3313	4.3324	0.0014
	Bottom	4.3321	4.3316		0.0005
	Taper	0.0009	0.0005		
3	Top	4.3324	4.3312		0.0012
	Middle	4.3326	4.3309	4.3324	0.0017
	Bottom	4.3322	4.3313		0.0009
	Taper	0.0004	0.0004		
4	Top	4.3322	4.3315		0.0007
	Middle	4.3326	4.3312	4.3324	0.0014
	Bottom	4.3321	4.3317		0.0004
	Taper	0.0005	0.0005		
5	Top	4.3323	4.3314		0.0009
	Middle	4.3326	4.3312	4.3323	0.0014
	Bottom	4.3319	4.3318		0.0001
	Taper	0.0007	0.0006		
6	Top	4.3323	4.3320		0.0003
	Middle	4.3322	4.3318	4.3320	0.0004
	Bottom	4.3317	4.3320		0.0003
	Taper	0.0006	0.0002		

Cylinder Bore Diameter Changes, in

Cylinder	Depth	Tranverse (TD)	Longitude (LD)	Avg Bore Dia. Change (TD@MID + TD@BOT)/2
1	Top	0.0019	0.0001	
	Middle	0.0004	0.0009	0.0004
	Bottom	0.0004	0.0007	
2	Top	0.0022	0.0010	
	Middle	0.0013	0.0019	0.0006
	Bottom	0.0000	0.0011	
3	Top	0.0016	0.0017	
	Middle	0.0011	0.0024	0.0006
	Bottom	0.0000	0.0014	
4	Top	0.0013	0.0013	
	Middle	0.0013	0.0019	0.0007
	Bottom	0.0001	0.0009	
5	Top	0.0016	0.0016	
	Middle	0.0013	0.0020	0.0008
	Bottom	0.0003	0.0008	
6	Top	0.0011	0.0002	
	Middle	0.0003	0.0007	0.0006
	Bottom	0.0009	0.0002	
Avgerage All Cylinders	Top	0.0016	0.0010	
	Middle	0.0010	0.0016	
	Bottom	0.0003	0.0009	

Piston Skirt to Bore Clearance, in

	Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
Pre - Test	1	4.3320	4.3272	0.0048
	2	4.3318	4.3276	0.0041
	3	4.3319	4.3277	0.0042
	4	4.3317	4.3278	0.0038
	5	4.3318	4.3275	0.0042
	6	4.3323	4.3275	0.0048
Post - Test	1	4.3320	4.3270	0.0050
	2	4.3324	4.3271	0.0053
	3	4.3324	4.3274	0.0050
	4	4.3324	4.3276	0.0047
	5	4.3323	4.3271	0.0052
	6	4.3320	4.3270	0.0050

Top and Second Ring Radial Wear, in

Top Ring				
Cylinder	Position	Before	After	Delta
1	1	0.17085	0.17080	0.00005
	2	0.17055	0.17040	0.00015
	3	0.17095	0.17085	0.00010
	4	0.16980	0.16955	0.00025
	5	0.17085	0.17080	0.00005
2	1	0.17140	0.17135	0.00005
	2	0.17135	0.17135	0.00000
	3	0.17120	0.17120	0.00000
	4	0.17025	0.17020	0.00005
	5	0.17105	0.17105	0.00000
3	1	0.17160	0.17160	0.00000
	2	0.17130	0.17120	0.00010
	3	0.17170	0.17165	0.00005
	4	0.17235	0.17225	0.00010
	5	0.17210	0.17205	0.00005
4	1	0.17255	0.17255	0.00000
	2	0.17160	0.17155	0.00005
	3	0.17205	0.17200	0.00005
	4	0.17235	0.17230	0.00005
	5	0.17240	0.17225	0.00015
5	1	0.17125	0.17120	0.00005
	2	0.17125	0.17120	0.00005
	3	0.17150	0.17145	0.00005
	4	0.17040	0.17025	0.00015
	5	0.17125	0.17115	0.00010
6	1	0.17095	0.17095	0.00000
	2	0.17185	0.17185	0.00000
	3	0.17230	0.17215	0.00015
	4	0.17025	0.17025	0.00000
	5	0.17090	0.17090	0.00000
*Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error				

Maximum	0.00025
Average	0.00006

Second Ring				
Cylinder	Position	Before	After	Delta
1	1	0.16995	0.16975	0.00020
	2	0.16895	0.16885	0.00010
	3	0.16690	0.16990	-0.00300
	4	0.16795	0.16795	0.00000
	5	0.16920	0.16910	0.00010
2	1	0.16860	0.16860	0.00000
	2	0.16935	0.16930	0.00005
	3	0.17065	0.17045	0.00020
	4	0.16900	0.16875	0.00025
	5	0.16790	0.16785	0.00005
3	1	0.16970	0.16965	0.00005
	2	0.16885	0.16875	0.00010
	3	0.16925	0.16910	0.00015
	4	0.17045	0.17040	0.00005
	5	0.16960	0.16960	0.00000
4	1	0.16750	0.16750	0.00000
	2	0.16805	0.16790	0.00015
	3	0.16905	0.16895	0.00010
	4	0.16895	0.16885	0.00010
	5	0.16745	0.16735	0.00010
5	1	0.16950	0.16940	0.00010
	2	0.16790	0.16790	0.00000
	3	0.16820	0.16820	0.00000
	4	0.17015	0.17015	0.00000
	5	0.16945	0.16945	0.00000
6	1	0.16990	0.16980	0.00010
	2	0.17070	0.17070	0.00000
	3	0.16855	0.16855	0.00000
	4	0.16910	0.16900	0.00010
	5	0.16840	0.16840	0.00000
*Note - Measurements with a negitive delta value, shown in italics, are considered pre-test measurements error				

Maximum	0.00025
Average	-0.00003

Piston Ring Gap Measurements, in

Cylinder	Ring No.	Before	After	Delta
1	1	0.018	0.015	-0.003
	2	0.052	0.050	-0.002
	3	0.018	0.020	0.002
2	1	0.018	0.016	-0.002
	2	0.054	0.051	-0.003
	3	0.018	0.018	0.000
3	1	0.018	0.016	-0.002
	2	0.055	0.053	-0.002
	3	0.018	0.019	0.001
4	1	0.018	0.017	-0.001
	2	0.052	0.051	-0.001
	3	0.018	0.020	0.002
5	1	0.018	0.017	-0.001
	2	0.052	0.051	-0.001
	3	0.018	0.021	0.003
6	1	0.018	0.017	-0.001
	2	0.052	0.051	-0.001
	3	0.018	0.020	0.002

Ring No. 1 max increase	-0.001
Ring No. 2 max increase	-0.001
Ring No. 3 max increase	0.003

Ring No. 1 avg increase	-0.002
Ring No. 2 avg increase	-0.002
Ring No. 3 avg increase	0.002

Piston Ring Mass, grams

Cylinder	Ring No.	Before	After	Delta
1	1	28.2300	28.2226	0.0074
	2	26.9232	26.9191	0.0041
	3	16.8362	16.8292	0.0070
2	1	28.3608	28.3495	0.0113
	2	27.0596	27.0546	0.0050
	3	16.7351	16.7275	0.0076
3	1	28.4738	28.4656	0.0082
	2	27.1022	27.0991	0.0031
	3	17.4968	17.4888	0.0080
4	1	28.5471	28.5351	0.0120
	2	27.2028	27.1984	0.0044
	3	16.7075	16.7007	0.0068
5	1	28.3362	28.3272	0.0090
	2	27.1016	27.0982	0.0034
	3	16.7891	16.7826	0.0065
6	1	28.3406	28.3318	0.0088
	2	27.2102	27.2070	0.0032
	3	17.5251	17.5163	0.0088

Ring No. 1 max decrease	0.0120
Ring No. 2 max decrease	0.0050
Ring No. 3 max decrease	0.0088

Ring No. 1 avg decrease	0.0095
Ring No. 2 avg decrease	0.0039
Ring No. 3 avg decrease	0.0074

Connecting Rod Bearing Weight Loss, grams

Rod Bearing	Shell	Before	After	Change
1	Top	75.7098	75.6909	0.0189
	Bottom	75.7759	75.7704	0.0055
2	Top	75.7826	75.7621	0.0205
	Bottom	76.1524	76.1409	0.0115
3	Top	75.4131	75.3909	0.0222
	Bottom	75.6658	75.6567	0.0091
4	Top	75.3407	75.3161	0.0246
	Bottom	75.4955	75.4824	0.0131
5	Top	75.6626	75.6438	0.0188
	Bottom	75.3009	75.2873	0.0136
6	Top	75.5645	75.5434	0.0211
	Bottom	75.5083	75.4946	0.0137

Maximum	0.0246
Average	0.0160

Main Bearing Weight Loss, grams

Main Bearing	Shell	Before	After	Change
1	Top	73.6049	73.6000	0.0049
	Bottom	80.9897	80.9875	0.0022
2	Top	73.4853	73.4933	-0.0080
	Bottom	81.0906	81.0862	0.0044
3	Top	74.0065	74.0048	0.0017
	Bottom	81.8293	81.8248	0.0045
4	Top	73.5080	73.5067	0.0013
	Bottom	81.8535	81.8503	0.0032
5	Top	73.3391	73.3348	0.0043
	Bottom	81.2934	81.2900	0.0034
6	Top	145.6079	145.5817	0.0262
	Bottom	81.9935	81.9890	0.0045
7	Top	73.5946	73.5928	0.0018
	Bottom	81.4292	81.4278	0.0014

Maximum	0.0262
Average	0.0040

Photographs

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Piston Skirt Thrust - Best Cyl 2

Piston Skirt Anti-thrust - Best Cyl 2

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

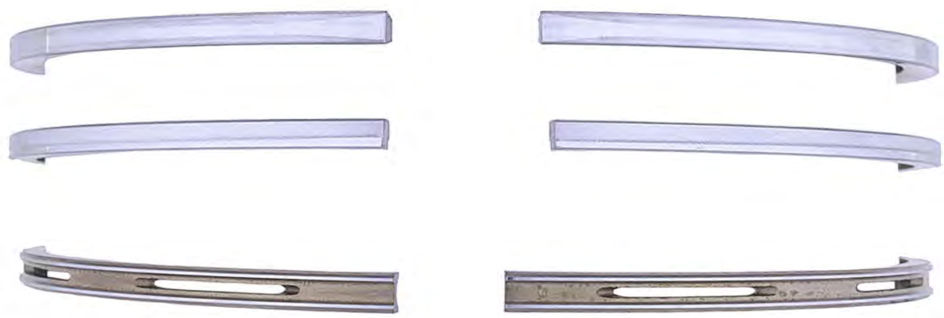
Piston Skirt Thrust - Worst Cyl 3

Piston Skirt Anti-thrust - Worst Cyl 3

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Piston Rings - Best Cyl 1



Piston Rings - Worst Cyl 2

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Piston Undercrown - Best Cyl 2

Piston Undercrown - Worst Cyl 3

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Engine Block Cylinder Bore - Best Cyl 2T

Engine Block Cylinder Bore - Worst Cyl 5T

Oil Code:	LO-241026	EOT Date:	12/17/09
Test No.:	LO241026-C71-NATO-400	Test Hours:	400

Crossheads - 1,2,3,4,5,6

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Intake and Exhaust Valve - Best Cyl 1

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Intake and Exhaust Valve - Worst Cyl 6

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Rod Bearings

CAT C7 - NATO CYCLE

Oil Code:	LO-241026	**EOT Date:**	12/17/09
Test No.:	LO241026-C71-NATO-400	**Test Hours:**	400

Main Bearings

Test Fuel Properties

AGE REFINING, INC.

Product Name: JP-8

Tank: 424
Batch: 2009-CU
Date: 10/19/09
MIL-DTL-83133E

7811 S. Presa
San Antonio, Texas 78223
(210) 532-5300
(210) 532-2220 Fax

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
Color, Saybolt	D 156		Report	+17
Total Acid No. mg KOH/g	D 3242		0.015	0.004
Aromatics, vol%	D 1319		25	15.2
Olefins, vol%	D 1319		5.0	0.9
Naphthalenes, vol%	D 1840		3.0	VR
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.011
Distillation temperature, °C	D 86			
•IBP			Report	141
•10% recovered, temp			205	162
•20% recovered, temp			Report	166
•50% recovered, temp			Report	192
•90% recovered, temp			Report	244
•End Point, temp			300	255
•Residue, vol%			1.5	1.0
•Loss, vol%			1.5	0.2
Flash Point, °F	D 93	100		106
Gravity, API at 15°C	D 1298	51.0	37.0	45.7
Freeze Point °C	D 2386		-47	-47.90
Viscosity at -20°C	D 445		8.0	4.57
Heat of Combustion, Btu/lb	D 3338	18,400		18,646
Hydrogen content, mass%	D 3701	13.4		14.05
Smoke Point, mm	D 1322	19		25.0
Copper strip corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test at 275°C	D 3241			
•Change in pressure drop, mmHg			25	0.0
•Tube deposit code			3	1
Existent gum, mg/100 mL	D 381		7	0.4
Particulate matter, mg/L	D 5452		1	0.22
Filtration time, minutes	D 5452		15	4
Water reaction	D 1094			
•Interface rating			1b	1
MSEP	D 3948	70		92
Conductivity, pS/m		12	22.4	12.29
Moisture, ppm	D 6304		Report	25
Fuel System Icing Inhibitor	D 5006	0.10	0.15	0.105
Calculated Cetane Index	D 976		Report	42.6
Stadis 450	D2624	150	450	

Report Date: 10/19/09

Analysis performed by : __

* Diethylene Glycol Monomethyl Ether
** Stadis 450

AF 7100
Tk #AL 32
P 2 FY 2010
10 22-2009
ATTN Robert Warden 3270

AGE Refining, Inc.

Product Name: JP-8

Tank: 424
Batch: 2009-DO
Date: 12/11/09
MIL-DTL-83133E

7811 S. Presa
San Antonio, Texas 78223
(210) 532-5300
(210) 532-7222 Fax

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
		Min	Max	Results
Color, Saybolt	D 156		Report	+19
Total Acid, mg KOH/g	D 3242		0.015	0.011
Aromatics, vol%	D 1319		25	14.9
Olefins, vol%	D 1319		5.0	0.7
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.008
Distillation temperature, °C	D 86			
•IBP			Report	146
•10% recovered, temp			205	163
•20% recovered, temp			Report	170
•50% recovered, temp			Report	194
•90% recovered, temp			Report	243
•End Point, temp			300	266
•Residue, vol%			1.5	1.3
•Loss, vol%			1.5	0.0
Flash Point, °F	D 93	100		102
Gravity, API, at 15°C	D 1298	51.0	37.0	46.9
Freeze Point, °C	D 2386		-47	-47.50
Viscosity @ -20°C	D 445		8.0	3.41
Heat of combustion, BTU/lb	D 3338	18,400		18,654
Hydrogen content, mass%	D 3701	13.4		14.03
Smoke Point, mm	D 1322	19		26.0
Copper corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test @ 275° C	D 3241			
• Pressure drop, mm Hg			25	0.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	0.2
Particulate matter, mg/L	D 5452		1	0.42
Filtration time, minutes	D 5452		15	5
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		71
Corrosion Inhibitor, Nalco 5403 g/m³		12	22.5	17.8
Moisture, ppm	D 6304		Report	89
Fuel System Icing Inhibitor*	D 5006	0.10	0.15	0.121
Calculated Cetane Index	D 976		Report	44.9
SDA** pS/m	D2624	150	450	

Report Date: 12/11/09

Analysis performed by: __

* Diethylene Glycol Monomethyl Ether
** Stadis 450

APPENDIX E

HTV - DDC Series 60 Engine

Test Number: 06R0772887-A

Test Procedure: 210 hr Tactical Wheeled Vehicle

EVALUATION OF MIL-PRF-46167 MULTIPURPOSE ARCTIC LUBRICANT

WORK DIRECTIVE NO. 42

HTV - DDC Series 60 Engine

Test Lubricant: AL-27015-L
Synthetic OEA-30
Test Fuel: JP-8
Test Number: 06R0772887-A
Start of Test: August 14, 2006
End of Test: October 10, 2006
Test Duration: 234 hours
Test Procedure: 210 hr Tactical Wheeled Vehicle

Conducted for

U.S. Army Tank-Automotive RD&E Center
Force Projection Technologies
Warren, Michigan 48397-5000

Approved by:

Edwin C. Owens, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI®)

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Introduction

This test was conducted at Southwest Research Institute (SwRI) in support of work directive number 42—Evaluation of Multipurpose Arctic Lubricant OEA-30. The purpose of this test was to lubricant performance in a HTV - DDC Series 60 Engine operated at high oil sump temperature. A modified version of the 210 hr Tactical Wheeled Vehicle test procedure was followed.

Test Engine

The test engine was a HTV – Detroit Diesel Corporation Series 60 engine DEDEC III equipped with air compressor and Jake Brake assembly. The Jake Brake assembly was physically installed but was electrically de-activated for this test. The engine was disassembled, measured for pre-test wear measurements, clearances and specifications verified, and re-assembled following the guidelines in the service manual.

Test Stand Configuration

The engine was coupled to a suitable dynamometer capable of absorbing the required load. External liquid-to-liquid heat exchangers were utilized for control of oil sump temperature and coolant temperature. Boost air temperature was controlled using a liquid to air heat exchanger.

Engine Run-in

Before beginning the test cycle, the engine was equipped with new oil filters and filled with a fresh oil charge of 38 quarts and ran-in using the following schedule.

Duration	Ends when Water Jacket Outlet > 169 °F	5 minutes	10 minutes	12 minutes
Speed, rpm	1500 ± 25	1500 ± 10	1750 ± 10	2100 ± 10
Torque, ft-lb	Minimum	800 ± 25	1075 ± 25	Full Load
Coolant Out, °F	170	205 ± 3	205 ± 3	205 ± 3
Oil Sump, °F	255 maximum	255 maximum	255 maximum	255 maximum

Pre-test Engine Performance Checks

At the completion of the run-in, new oil filters were installed and a fresh oil charge of 38 quarts was added to the oil sump. A full load power curve was conducted starting at 900 rpm and ending at 2100 rpm using 100 rpm steps.

Test Cycle

The standard 210 hr Tactical Wheeled Vehicle Cycle was modified to provide for 20 hours of continuous running followed by a 4-hour soak. The first 18 hours of each 20-hour running segment was composed of 6 cycles of 3 hours of continuous operation. Each cycle consisted of 2 hours of operation at rated speed and full power conditions followed by a 1 hour of operation at idle conditions. The last 2 hours of each 20-hour running segment was composed of 2 hours at rated speed and full power conditions. Test time was accumulated only during the running segment. At 24 hours of running time, the engine air compressor experienced a catastrophic failure when one of the pistons developed a hole and increased engine pressure tripped a built-in engine stop alarm. Due to the possibility of oil contamination from metal debris, the air compressor was replaced, engine lubricant recharged and the test was re-started and extended to 234 hours of running time to complete a full 210 hours on the engine oil recharge.

Test coolant was a 60/40 blend of Prestone II antifreeze and de-ionized water. Test oil was AL-27015-L Multipurpose Arctic Lubricant OEA-30. Test fuel was JP-8. Coolant and oil temperatures were elevated to simulate desert warfare conditions but limited to a maximum oil sump temperature of 260°F.

Test Cycle Operational Targets

Parameter	Rated Speed / Full Power	Idle
Duration, min.	120	60
Engine Speed, rpm	2100 ± 25	900 ± 25
Water Jacket Outlet, ° F	215 ± 3	110 ± 3
Oil Sump, °F	255 ± 3	110 ± 3[1]

Oil Level Checks

Every 20 hours of operation the engine was stopped and allowed to soak for 4 hours. The oil level was checked and recorded at 20 minutes into the soak period. Fresh oil was then added to restore the oil level to the full mark.

Oil Sampling

Oil samples were obtained every 14 hours of test operation. At 70, 140, and 210 hours 16 fluid ounce samples were obtained. After obtaining the 70 and 140 hour sample, 16 fluid ounces of fresh oil were added to the sump. For all other sample times, an 8 fluid ounce sample was obtained followed by 8 ounces of fresh oil added to the sump.

Post-test Engine Performance Checks

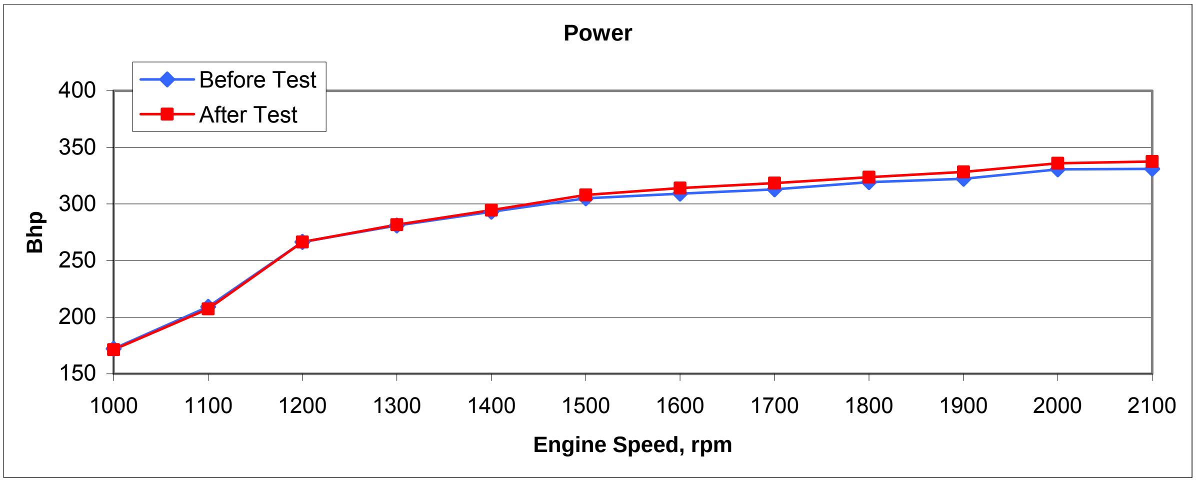
At the completion of the 210-hour test, a full load power curve was conducted starting at 900 rpm and ending at 2100 rpm using 100 rpm steps.

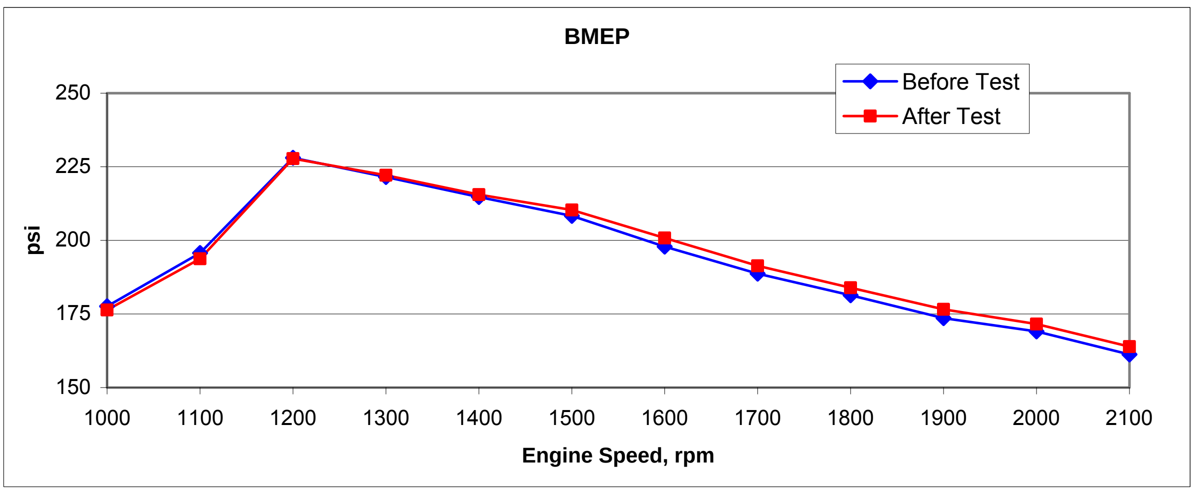
[1] Thermal loading in conjunction with oil sump capacity of 38 quarts and low oil flow at idle prevented reaching the target oil temperature during idle.

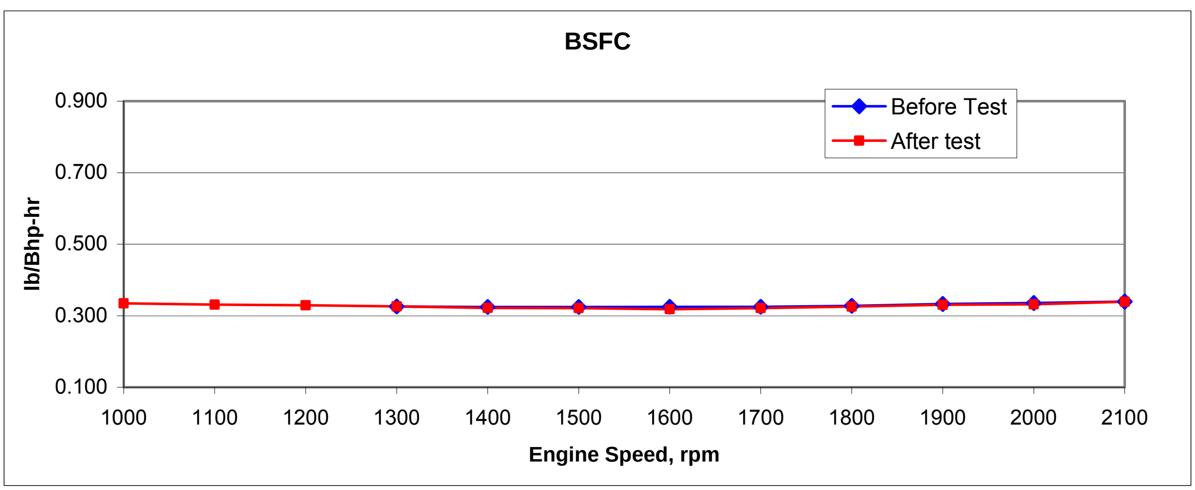
Engine Operating Conditions Summary

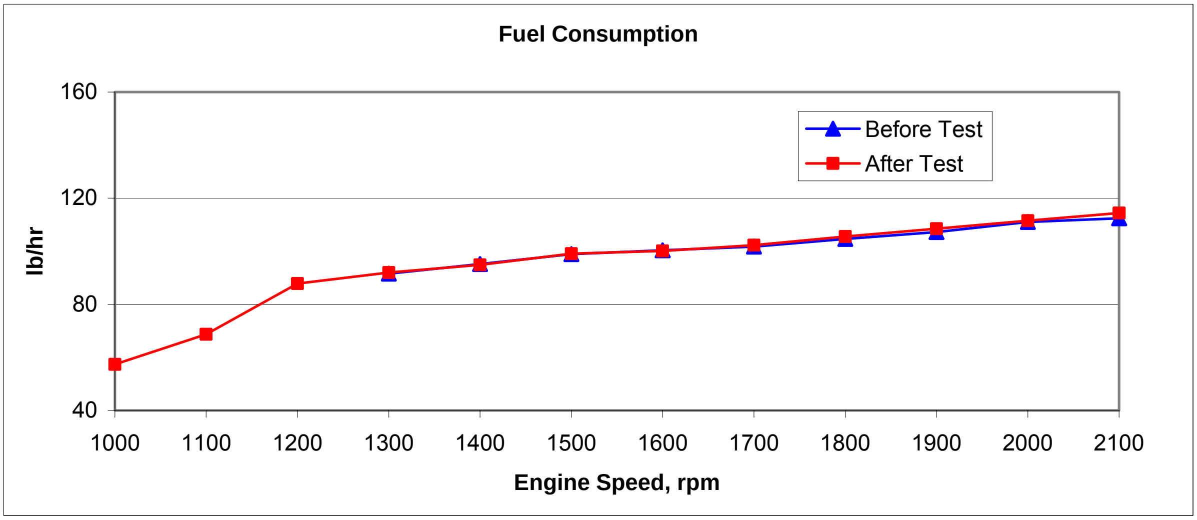
	Maximum Power Mode (2100 rpm)		Idle Mode	
	Mean	Standard Deviation	Mean	Standard Deviation
Engine Speed, rpm	2101.0	1.3	900.0	20.3
Torque, ft-lb	837.0	6.8	55.0	19.9
Fuel Consumption, lb/hr	113.8	2.7	8.6	4.0
Observed Power, Bhp	335.0	3.0	9.6	8.0
BSFC, lb/BHP-hr	0.340	0.0	0.916	0.4
Temperatures, °F				
Exhaust Cyls. 1-3 Before Turbo	1019.0	14.3	255.7	25.9
Exhaust Cyls. 4-6 Before Turbo	1274.3	238.3	643.9	588.7
Exhaust After Turbo	869.6	14.8	249.0	27.7
Water Jacket Inlet	207.6	0.9	104.9	2.8
Water Jacket Outlet	215.0	0.8	110.0	2.9
Oil Sump	250.2	8.1	141.2	11.3
Fuel at Filter	119.7	2.9	89.2	3.2
Inlet Air	125.0	1.4	86.5	4.0
Airbox	88.6	10.1	81.8	7.5
Exhaust Port Cylinder 1	923.7	13.1	232.2	26.1
Exhaust Port Cylinder 2	930.6	12.7	239.7	23.6
Exhaust Port Cylinder 3	967.4	13.8	247.0	24.1
Exhaust Port Cylinder 4	1003.2	25.3	256.0	26.2
Exhaust Port Cylinder 5	1059.1	66.8	203.0	63.7
Exhaust Port Cylinder 6	1023.2	13.2	237.9	28.9
Pressures				
Exhaust Before Turbo, psi	13.2	0.3	0.6	0.2
Exhaust After Turbo, psi	2.0	0.0	0.1	0.0
Compressor Discharge, psi	15.3	0.5	0.8	0.3
Oil Gallery, psi	48.1	1.2	50.3	1.4
Intake Pressure, psiA	14.1	0.1	14.3	0.1
Barometric Pressure, psiA	14.4	0.1	14.4	0.1
Intake Pressure, psi	14.1	0.1	15.2	0.3

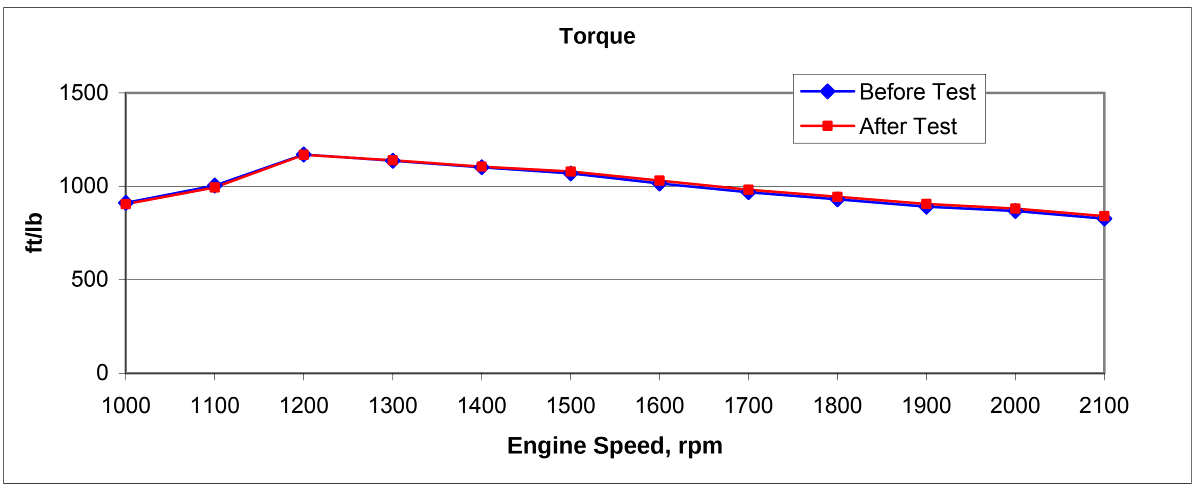
Performance Curves








Fuel Consumption
lb/hr
160
120
80
40
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Engine Speed, rpm
Before Test
After Test


Torque
ft/lb
1500
1000
500
0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Engine Speed, rpm
Before Test
After Test

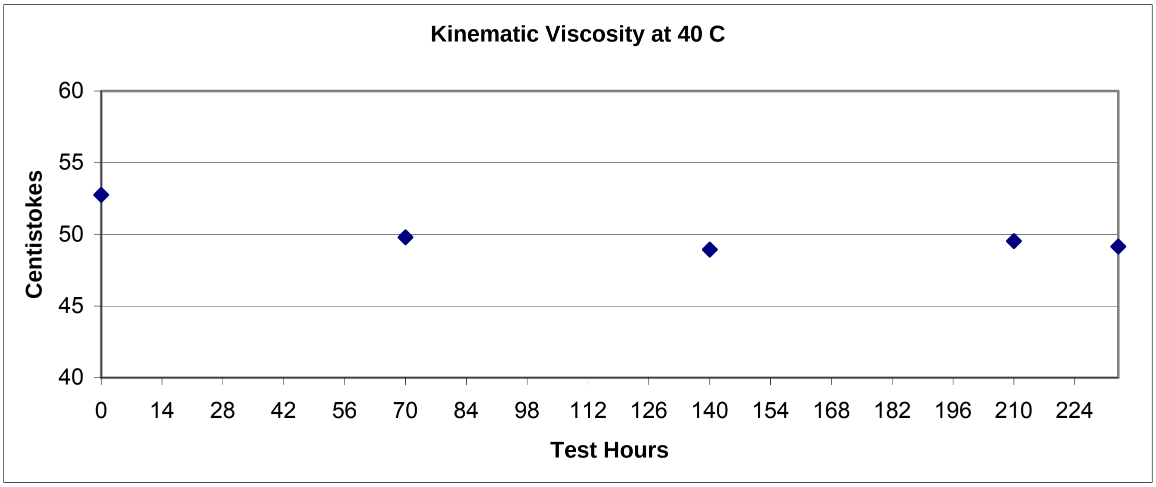
Emissions Data

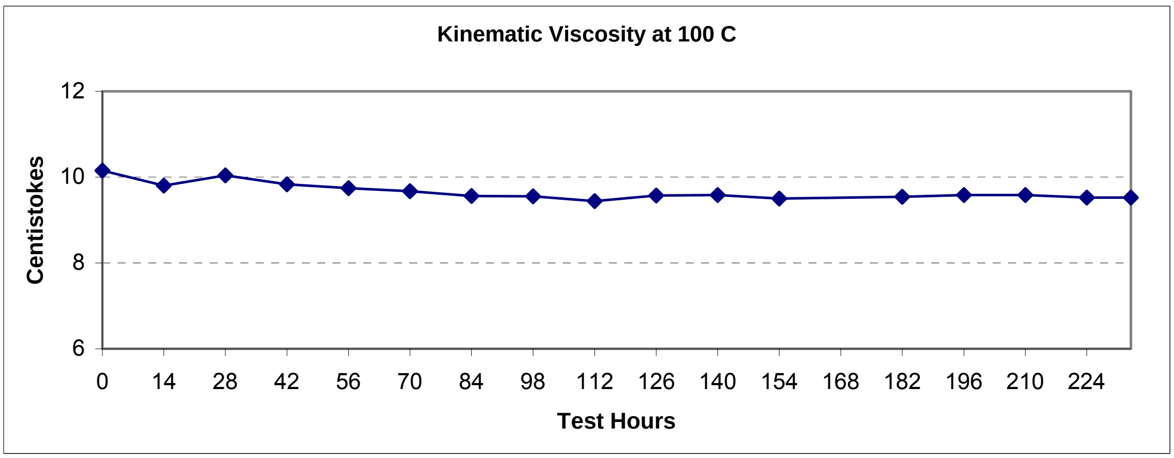
Emissions data are not available

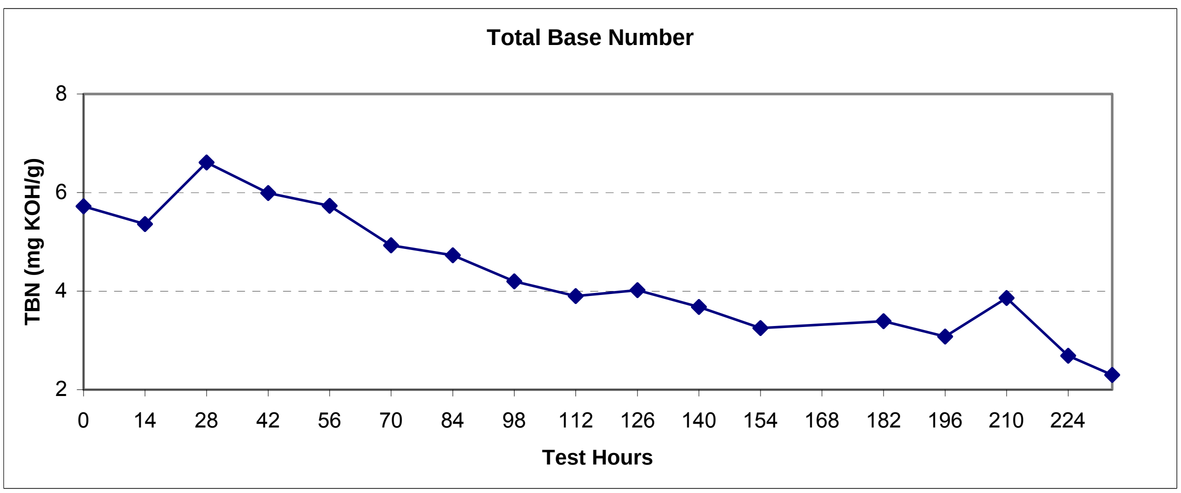
New and Used Lubricant Analyses

Test Hours	0	14	28	42	56	70	84	98	112	126	140	154	182	196	210	224	234
Total Base Number, mg KOH/g (ASTM D4739)	5.72	5.36	6.61	5.99	5.73	4.93	4.73	4.2	3.9	4.02	3.68	3.25	3.39	3.08	3.86	2.69	2.3
Total Acid Number, mg KOH/g (ASTM D664)	3.15	2.05	2.3	2.24	2.21	2.22	2.2	2.08	2.21	2.18	2.19	2.18	2.34	2.36	2.28	2.37	2.5
Kinematic Viscosity at 100°C cst (ASTM D445)	10.15	9.8	10.04	9.83	9.74	9.67	9.56	9.55	9.44	9.57	9.58	9.5	9.54	9.58	9.58	9.52	9.52
Kinematic Viscosity at 40°C cst (ASTM D445)	52.76					49.8					48.94				49.53		49.15
VI Index (ASTM D2270)						184					185				182		182
API Gravity (ASTM D4052)		27.5	27.5	27.5	27.4	27.4	27.4	27.3	27.3	27.2	27.2	27.3	27.1	27	27	26.9	26.9
Density (ASTM D4052)		0.8891	0.8889	0.8891	0.8894	0.8896	0.8898	0.89	0.8903	0.8915	0.8907	0.8903	0.8915	0.8917	0.8919	0.8922	0.8924
Soot (TGA)		0.364	0.258	0.305	0.334	0.279	0.316	0.5	0.351	0.339	0.443	0.379	0.537	0.561	0.48	0.631	0.464
Oxidation, Abs./cm (ASTM E168)		-0.28	0.28	0	-0.37	2.12	0.92	2.86	4.33	4.33	4.98	8.11	8.39	8.85	10.6	6.93	11.28
Nitration, Abs./cm (ASTM E168)																	
Wear Metals by ICP, ppm (ASTM D5185)																	
Fe	3	8	5	7	9	10	13	14	17	19	20	22	26	28	30	33	35
Cu	<1	2	<1	2	2	3	3	4	4	4	4	4	5	5	6	6	7
Al	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1	1	<1	<1
Si	4	7	3	4	4	6	5	6	6	8	8	12	10	10	9	8	9
Ag	<1	6	<1	<1	<1	1	<1	5	<1	<1	<1	<1	<1	<1	<1	<1	<1
Sn	<1	8	<1	1	2	2	2	2	3	3	3	3	4	4	4	5	5
Pb	<1	3	1	1	2	4	3	4	3	3	4	4	5	5	6	6	6

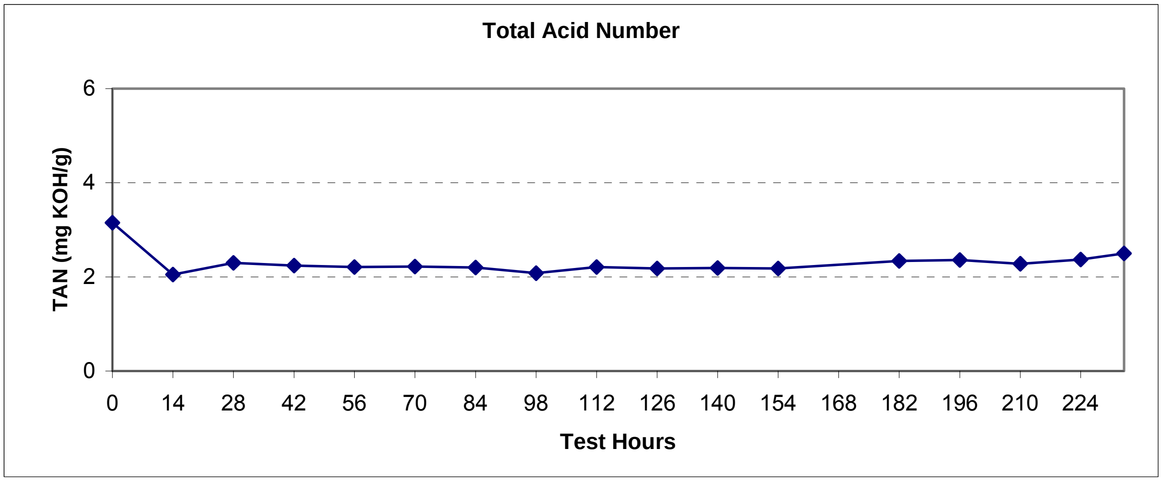
New and Used Oil Analysis Trends

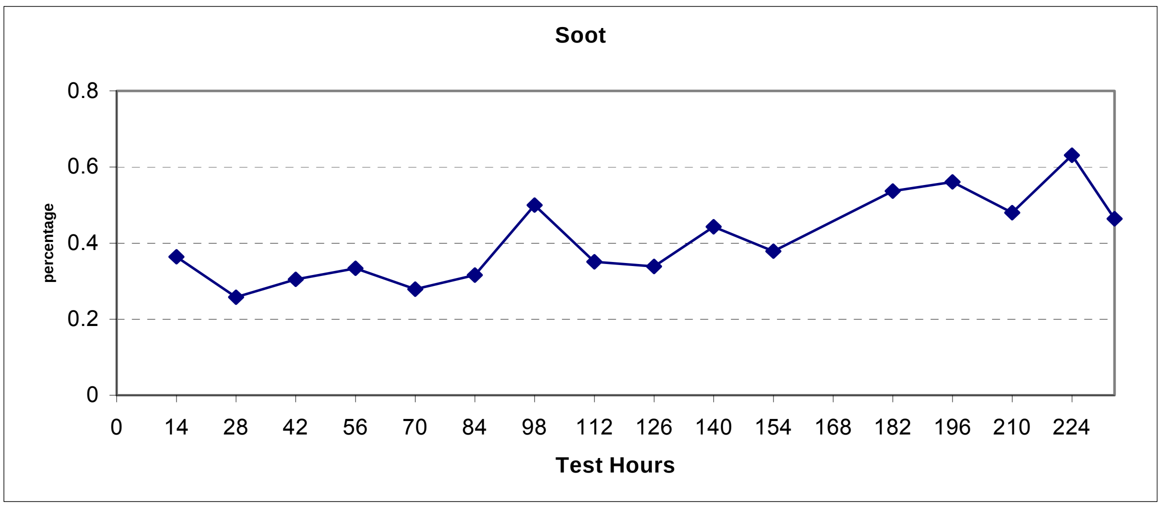


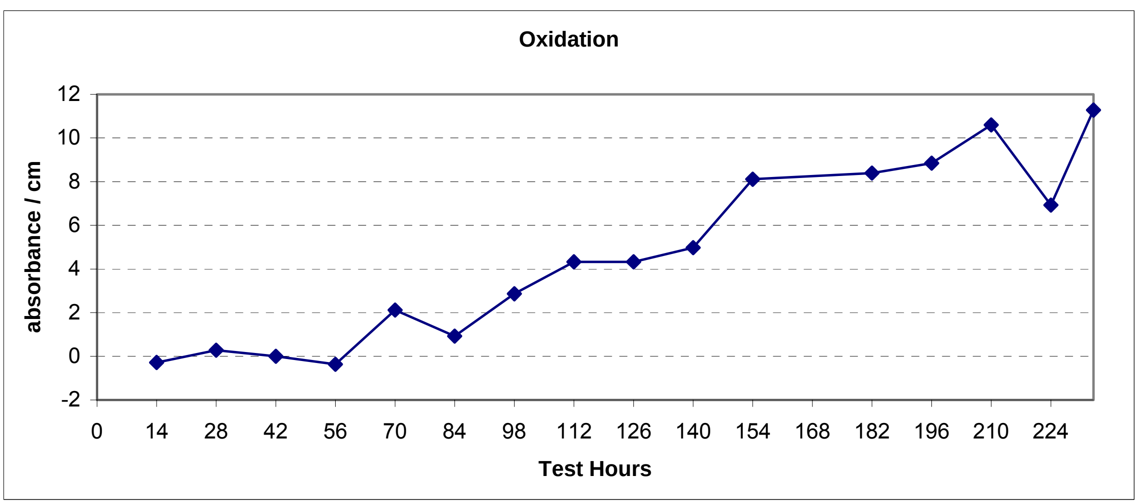




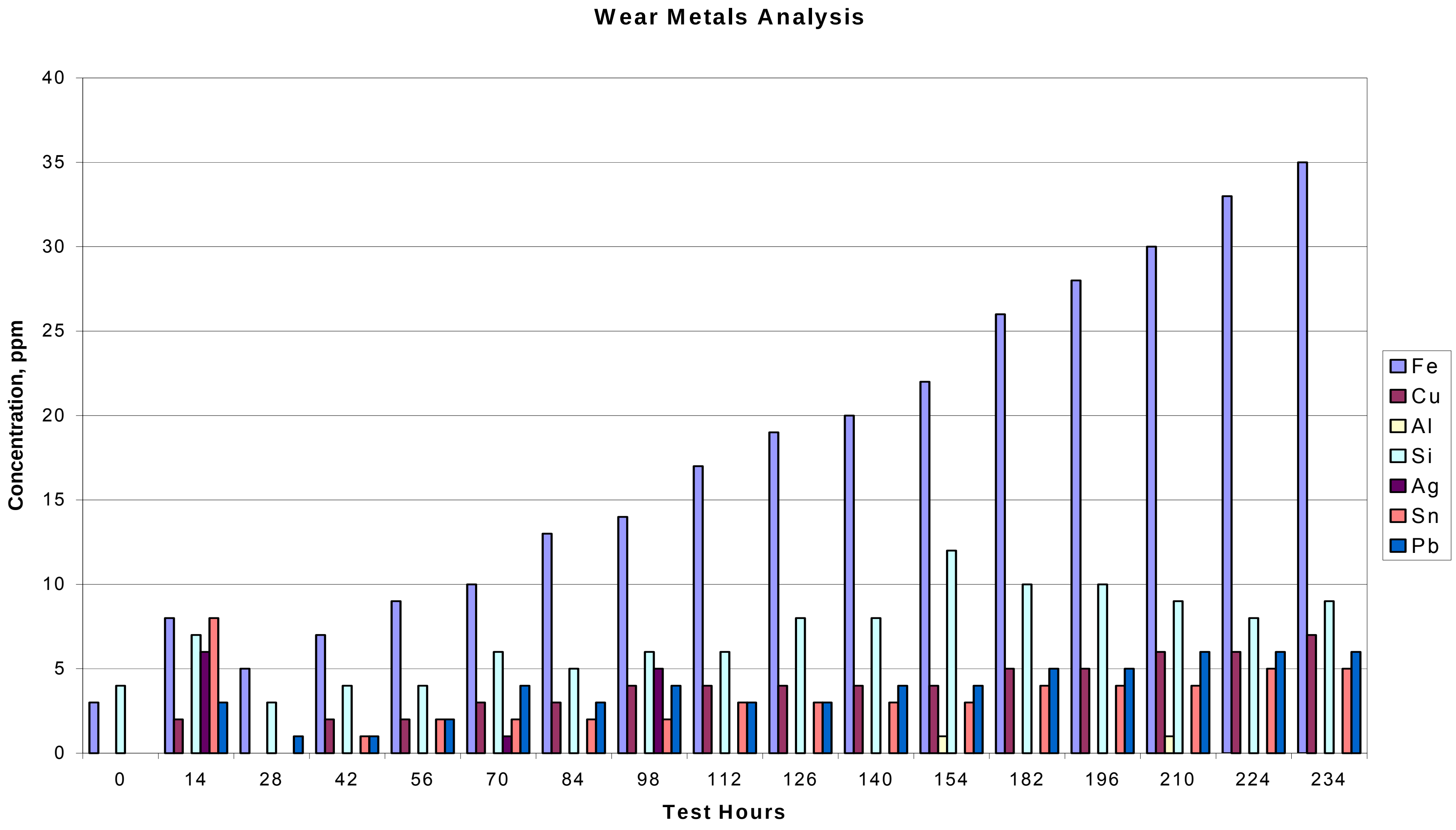
New and Used Oil Analysis Trends







New and Used Oil Wear Metal Trends



Oil Consumption Data

Data are not available.

Post Test Engine Conditions and Deposits

Evaluation	Cylinder Number						
	1	2	3	4	5	6	Average
Piston Ring Sticking							
No. 1	None	None	None	None	None	None	None
No. 2	None	None	None	None	None	None	None
No. 3	None	None	None	None	None	None	None
Scuffing, % Area							
No. 1 Ring	0	0	0	0	0	0	0
No. 2 Ring	0	0	0	0	0	0	0
No. 3 Ring	0	0	0	0	0	0	0
Piston Crown	0	0	0	0	0	0	0
Piston Skirt	0	0	0	0	0	0	0
Cylinder Liner	0	0	0	0	0	0	0
Piston Carbon Rating, Demerits							
No. 1 Groove	86.50	75.75	84.00	52.25	54.75	44.25	66.25
No. 2 Groove	---	0.25	1.00	---	2.50	7.00	2.69
No. 3 Groove	---	---	---	---	---	---	---
No. 1 Land	25.50	26.25	46.75	46.75	28.00	28.75	33.67
No. 2 Land	15.50	14.75	2.50	5.00	14.75	16.50	11.50
No. 3 Land	---	---	---	---	---	---	---
No. 4 Land	---	---	---	---	---	---	---
Cooling Gallery	---	---	---	---	---	---	---
Undercrown	---	---	---	---	---	---	---
Piston Lacquer Rating, Demerits							
No. 1 Groove	---	---	---	---	---	---	---
No. 2 Groove	2.10	2.61	3.39	4.00	3.48	2.92	3.08
No. 3 Groove	1.78	1.73	2.87	3.20	1.44	3.88	2.48
No. 1 Land	0.36	0.09	---	---	---	---	---
No. 2 Land	1.76	2.38	3.06	3.99	1.84	1.84	2.48
No. 3 Land	0.83	1.50	1.25	1.66	0.90	1.45	1.27
No. 4 Land	0.20	0.39	0.57	0.80	0.50	1.10	0.59
Cooling Gallery	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Undercrown	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Total Demerits	137.5	128.7	148.4	120.7	111.2	110.7	126.2
Miscellaneous							
Top Groove Fill, %	84	65	74	53	47	29	59
Intermediate Groove Fill, %	0	0	0	0	0	0	0
Top Land Heavy Carbon, %	2	2	29	29	4	5	11.8
Top Land Flaked Cabon, %	0	0	0	0	0	0	0
Exhaust Valve Tulip Deposits, merits							
Front	8.4	9.4	8.4	8.2	8.4	9.2	8.7
Rear	9.2	9.4	8.3	8.2	8.2	8.2	8.6
Intake Valve Tulip Deposits, merits							
Front	7.8	7.8	7.7	7.8	7.6	7.6	7.7
Rear	8.2	7.8	9.5	9.2	7.8	8.6	8.5

Engine Rebuilt Measurements

Cylinder Liners (Installed)	Minimum	Maximum	Average		Specified Limits
Inside Diameter	5.11895	5.1196	5.1192		5.118 to 5.120
Out of Round	0.0000	0.0002	0.0001		0.001 max
Taper	0.0001	0.0003	0.0002		
Piston Skirt Diameter	5.114	5.115	5.1147		
Piston Skirt to Cylinder Liner Clearance	0.0040	0.0053	0.0046		0.002 to 0.0072
Piston Ring End Gaps					
Top Ring	0.026	0.029	0.028		
Second Ring	0.036	0.039	0.037		
Oil Control Ring	0.022	0.024	0.024		
Ring to Groove Clearances					
Oil Control Ring	0.001	0.001	0.001		0.001 to 0.004
Piston Pin					
Piston Pin Diameter	1.7712	1.7713	1.7712		1.7712 to 1.7716
Pin Bore in Dome	1.7744	1.7748	1.7742		1.7728 to 1.7740
Bearing Clearances					
Connecting Rod Bearing to Journal	0.003	0.003	0.003		0.0016 to 0.0056
Main Bearing to Journal	0.005	0.005	0.005		0.0016 to 0.005
Camshaft Bearing to Journal	0.005	0.005	0.005		0.0035 to 0.0065

Cylinder Liner Bore Diameter Changes, in

Cylinder	Depth	T-AT	F-B	Individual Cylinder Average Change
1	Top	0.0001	-0.0002	
	Middle	0.0002	-0.0002	0.0000
	Bottom	0.0003	0.0000	
2	Top	0.0001	-0.0002	
	Middle	0.0002	-0.0003	0.0000
	Bottom	0.0001	0.0000	
3	Top	0.0000	-0.0001	
	Middle	0.0002	-0.0003	0.0000
	Bottom	0.0004	-0.0001	
4	Top	0.0001	-0.0002	
	Middle	0.0000	-0.0001	0.0000
	Bottom	0.0002	0.0000	
5	Top	0.0002	-0.0001	
	Middle	0.0001	-0.0002	0.0000
	Bottom	0.0004	-0.0001	
6	Top	0.0002	-0.0001	
	Middle	0.0003	-0.0002	0.0001
	Bottom	0.0004	-0.0001	
Average Change for All Cylinders	Top	0.0001	-0.0002	
	Middle	0.0002	-0.0002	
	Bottom	0.0003	-0.0001	
		Overall average change:	0.0000	

Cylinder Liner Wear By PDI Surface Analysis, µm

Cylinder	Front	Thrust	Back	Anti-thrust
1.00	3.04	5.00	3.03	3.49
2.00	2.00	1.74	1.69	2.30
3.00	2.11	3.21	2.66	1.40
4.00	3.42	2.75	3.22	2.14
5.00	2.97	2.14	3.74	4.19
6.00	2.17	2.22	3.14	2.68
Maximum Cylinder Liner Wear		5.00		
Average Cylinder Liner Wear		2.77		

Top Ring Radial Wear, in.

Cylinder Number	Position	Before	After	Delta
1	1	0.2011	0.2011	0.0000
	2	0.1999	0.1998	0.0001
	3	0.2004	0.2004	0.0000
	4	0.2001	0.1999	0.0002
	5	0.2006	0.2006	0.0000
2	1	0.1999	0.1996	0.0003
	2	0.2000	0.1999	0.0001
	3	0.1997	0.1996	0.0001
	4	0.1973	0.1973	0.0000
	5	0.1997	0.1995	0.0002
3	1	0.2050	0.2049	0.0001
	2	0.2028	0.2027	0.0001
	3	0.2058	0.2057	0.0000
	4	0.2067	0.2067	0.0000
	5	0.2060	0.2059	0.0001
4	1	0.2031	0.2029	0.0002
	2	0.2036	0.2035	0.0001
	3	0.2055	0.2054	0.0001
	4	0.2032	0.2030	0.0003
	5	0.2028	0.2026	0.0002
5	1	0.2010	0.2009	0.0001
	2	0.2009	0.2006	0.0003
	3	0.2019	0.2017	0.0002
	4	0.2011	0.2011	0.0000
	5	0.2025	0.2022	0.0004
6	1	0.2060	0.2008	0.0052
	2	0.1991	0.1989	0.0002
	3	0.1991	0.1989	0.0003
	4	0.1981	0.1930	0.0051
	5	0.1978	0.1971	0.0007
			maximum	0.0052
			average	0.0005

Piston Ring Gap Measurements, in.

Cylinder Number	Ring No.	Before	After	Delta
1	1	0.029	0.030	0.001
	2	0.037	0.038	0.001
	3	0.024	0.024	0.000
2	1	0.029	0.030	0.001
	2	0.038	0.039	0.001
	3	0.023	0.024	0.001
3	1	0.029	0.030	0.001
	2	0.036	0.038	0.002
	3	0.024	0.025	0.001
4	1	0.028	0.029	0.001
	2	0.037	0.038	0.001
	3	0.024	0.024	0.000
5	1	0.029	0.030	0.001
	2	0.037	0.038	0.001
	3	0.022	0.022	0.000
6	1	0.026	0.027	0.001
	2	0.039	0.040	0.001
	3	0.024	0.024	0.000
	Ring No. 1, maximum			0.001
	Ring No. 2, maximum			0.002
	Ring No. 3, maximum			0.001
	Ring No. 1, average			0.0010
	Ring No. 2, average			0.0012
	Ring No. 3, average			0.0006

Piston Ring Mass, grams

Cylinder Number	Ring No.	Before	After	Delta
1	1	42.8800	42.8538	0.0262
	2	42.2046	42.2003	0.0043
	3	29.0237	29.0163	0.0074
2	1	42.7724	42.7517	0.0207
	2	42.3140	42.3080	0.0060
	3	28.8231	28.8122	0.0109
3	1	43.8763	43.8413	0.0350
	2	42.3470	42.3470	0.0000
	3	28.9858	28.9858	0.0000
4	1	43.6786	43.6477	0.0309
	2	42.3223	42.3155	0.0068
	3	29.3477	29.3406	0.0071
5	1	43.1343	43.1057	0.0286
	2	42.3891	42.3816	0.0075
	3	29.2842	29.2792	0.0050
6	1	42.3342	42.2946	0.0396
	2	42.3625	42.3569	0.0056
	3	29.2725	29.2684	0.0041
	Ring No. 1, maximum			0.0396
	Ring No. 2, maximum			0.0075
	Ring No. 3, maximum			0.0109
	Ring No. 1, average			0.0302
	Ring No. 2, average			0.0050
	Ring No. 3, average			0.0126

Top Piston Ring Width, inches

Cylinder Number	Before	After	Delta
1	0.1500	0.1329	0.0172
2	0.1499	0.1313	0.0187
3	0.1498	0.1341	0.0157
4	0.1498	0.1343	0.0155
5	0.1498	0.1323	0.0176
6	0.1497	0.1302	0.0196

maximum	0.0196
average	0.0174

Top Piston Ring Plating Thickness, in.

Cylinder Number	Position	Before	After	Delta
1	1	0.01240	0.01190	0.00050
	2	0.01330	0.01300	0.00030
	3	0.01370	0.01330	0.00040
	4	0.01210	0.01195	0.00015
	5	0.01295	0.01270	0.00025
2	1	0.01345	0.01330	0.00015
	2	0.01400	0.01370	0.00030
	3	0.01535	0.01460	0.00075
	4	0.01310	0.01260	0.00050
	5	0.01335	0.01295	0.00040
3	1	0.01365	0.01315	0.00050
	2	0.01360	0.01310	0.00050
	3	0.01520	0.01460	0.00060
	4	0.01520	0.01485	0.00035
	5	0.01515	0.01450	0.00065
4	1	0.00970	0.00905	0.00065
	2	0.01050	0.01025	0.00025
	3	0.01325	0.01265	0.00060
	4	0.01275	0.01215	0.00060
	5	0.01130	0.01100	0.00030
5	1	0.00650	0.00610	0.00040
	2	0.00535	0.00510	0.00025
	3	0.00995	0.00940	0.00055
	4	0.00795	0.00770	0.00025
	5	0.00670	0.00580	0.00090
6	1	0.01280	0.01220	0.00060
	2	0.01320	0.01285	0.00035
	3	0.01370	0.01290	0.00080
	4	0.01370	0.01275	0.00095
	5	0.01310	0.01270	0.00040
			maximum	0.00095
			average	0.00047

Slipper Bushing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1	152.1085	151.9622	0.1463
2	152.7799	152.6844	0.0955
3	151.2145	151.0586	0.1559
4	151.5107	151.4061	0.1046
5	151.1209	151.0343	0.0866
6	151.9033	151.8460	0.0573
		maximum	0.1559
		average	0.1077

Camshaft Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	61.1775	61.1759	0.0016
1B	61.0064	61.0582	-0.0518
2T	61.1122	61.1111	0.0011
2B	61.0458	61.0318	0.0140
3T	61.0816	61.0796	0.0020
3B	61.1125	61.1044	0.0081
4T	61.2370	61.2365	0.0005
4B	61.0664	61.0616	0.0048
5T	61.1665	61.1651	0.0014
5B	61.0303	61.0228	0.0075
6T	61.1729	61.1697	0.0032
6B	61.0946	61.0864	0.0082
7T	61.0810	61.0762	0.0048
7B	61.1355	61.1307	0.0048
		maximum	0.0140
		average	0.0007

Connecting Rod Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	157.6615	157.6427	0.0188
1B	153.5185	153.4959	0.0226
2T	157.5188	157.0008	0.5180
2B	152.2787	152.2535	0.0252
3T	157.5868	157.5681	0.0187
3B	153.5673	153.5511	0.0162
4T	157.6641	157.6363	0.0278
4B	152.1968	152.1818	0.0150
5T	157.8311	157.8038	0.0273
5B	153.4724	153.4495	0.0229
6T	157.8688	157.8491	0.0197
6B	152.2342	152.1921	0.0421
		maximum	0.5180
		average	0.0645
		average without maximum	0.0223

Main Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	220.8329	221.2138	-0.3809
1B	249.1169	249.0958	0.0211
2T	221.2138	221.2028	0.0110
2B	249.2271	249.1954	0.0317
3T	220.8579	220.8473	0.0106
3B	249.1078	249.0246	0.0832
4T	221.3736	221.3624	0.0112
4B	249.2779	249.2029	0.0750
5T	220.5736	220.5626	0.0110
5B	249.0749	249.0395	0.0354
6T	246.8679	241.8515	5.0164
6B	249.6772	249.6516	0.0256
7T	220.2635	220.2464	0.0171
7B	249.5372	249.4901	0.0471
		maximum	5.0164
		average	0.3583
		average without maximum	-0.0001

Before Test Cylinder Liner Measurements, in

Cyl.	Depth	Transverse (TD)	Longitude (LD)	Average Bore Diameter	Out of Round
1	Top	5.1190	5.1192		0.0002
	Middle	5.1193	5.1194	5.1193	0.0001
	Bottom	5.1193	5.1193		0.0000
	Taper	0.0003	0.0002		
2	Top	5.1191	5.1191		0.0000
	Middle	5.1191	5.1192	5.1192	0.0001
	Bottom	5.1192	5.1191		0.0001
	Taper	0.0001	0.0001		
3	Top	5.1193	5.1193		0.0000
	Middle	5.1193	5.1194	5.1193	0.0001
	Bottom	5.1192	5.1193		0.0001
	Taper	0.0001	0.0001		
4	Top	5.1190	5.1192		0.0002
	Middle	5.1191	5.1191	5.1191	0.0000
	Bottom	5.1190	5.1189		0.0001
	Taper	0.0001	0.0003		
5	Top	5.1196	5.1196		0.0000
	Middle	5.1197	5.1197	5.1196	0.0000
	Bottom	5.1195	5.1195		0.0000
	Taper	0.0002	0.0002		
6	Top	5.1189	5.1190		0.0001
	Middle	5.1190	5.1191	5.1190	0.0001
	Bottom	5.1189	5.1190		0.0001
	Taper	0.0001	0.0001		
Average Bore Diameter = (TD@MID + TD@BOT)/2					

Piston Skirt to Cylinder Liner Clearance

Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
1	5.1193	5.1140	0.0053
2	5.1192	5.1150	0.0042
3	5.1193	5.1150	0.0043
4	5.1191	5.1140	0.0051
5	5.1196	5.1150	0.0046
6	5.1190	5.1150	0.0040

Specifications
Cylinder Liner Installed Inside Diameter 5.118" to 5.120"
Cylinder Liner Maximum Out of Round 0.001"
Piston Skirt to Cylinder Liner Clearance 0.002" to 0.0072"

After Test Cylinder Liner Measurements, in

Cyl.	Depth	Transverse (TD)	Longitude (LD)	Average Bore Diameter	Out of Round
1	Top	5.1191	5.1190		0.0001
	Middle	5.1195	5.1192	5.1196	0.0003
	Bottom	5.1196	5.1193		0.0003
	Taper	0.0005	0.0003		
2	Top	5.1192	5.1189		0.0003
	Middle	5.1193	5.1189	5.1193	0.0004
	Bottom	5.1193	5.1191		0.0002
	Taper	0.0001	0.0002		
3	Top	5.1193	5.1192		0.0001
	Middle	5.1195	5.1191	5.1196	0.0004
	Bottom	5.1196	5.1192		0.0004
	Taper	0.0003	0.0001		
4	Top	5.1191	5.1190		0.0001
	Middle	5.1191	5.1190	5.1192	0.0001
	Bottom	5.1192	5.1189		0.0003
	Taper	0.0001	0.0001		
5	Top	5.1198	5.1195		0.0003
	Middle	5.1198	5.1195	5.1199	0.0003
	Bottom	5.1199	5.1194		0.0005
	Taper	0.0001	0.0001		
6	Top	5.1191	5.1189		0.0002
	Middle	5.1193	5.1189	5.1193	0.0004
	Bottom	5.1193	5.1189		0.0004
	Taper	0.0002	0.0000		
Average Bore Diameter = (TD@MID + TD@BOT)/2					

PHOTOGRAPHS

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

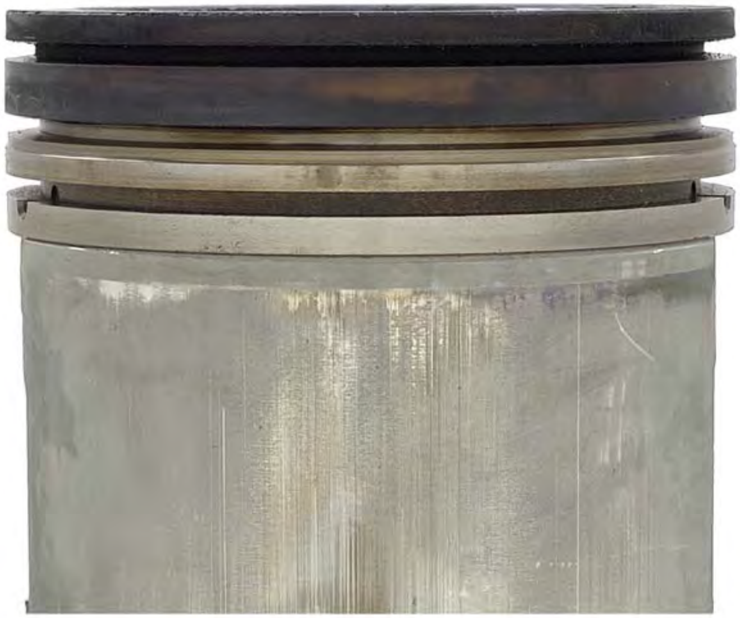
Piston Skirt Thrust - Best **Cyl. 5**

Piston Skirt Anti-thrust - Best **Cyl. 4**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Piston Skirt Thrust - Worst **Cyl. 2**



Piston Skirt Anti-thrust - Worst **Cyl. 2**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Piston Rings - Best **Cyl. 2**

Piston Rings - Worst **Cyl. 6**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

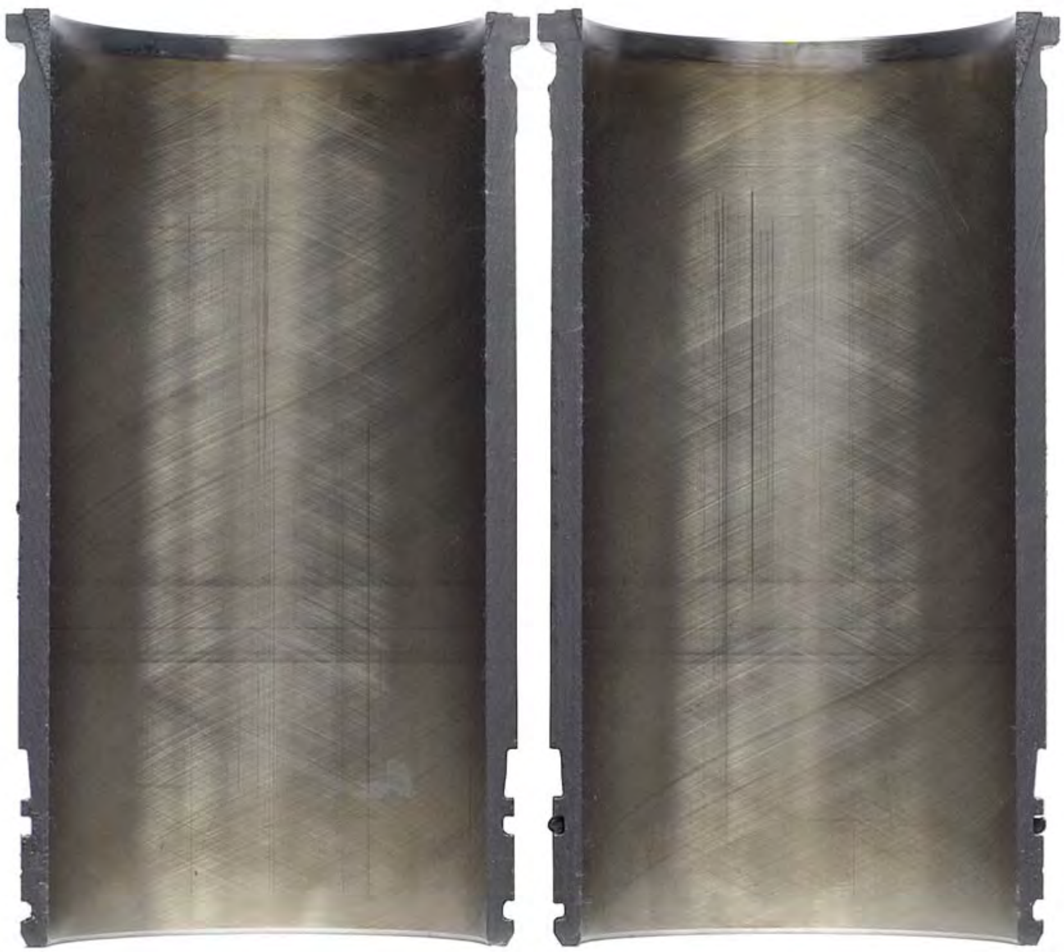
Piston Undercrown - Best **Cyl. 4**

Piston Undercrown - Worst **Cyl. 2**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Cylinder Sleeves Thrust / Anti-thrust - Best **Cyl. 2**



Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	EOT Date:	10/18/06
Test No.:	06R0772887-A	Test Length:	234

Cylinder Sleeves Thrust / Anti-thrust - Worst **Cyl. 1**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Exhaust and Intake Valve - Best Cyl. 2

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Exhaust and Intake Valve - Worst Cyl. 5

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Slipper Bushings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Main Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Rod Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Camshaft Bearings

APPENDIX F

HTV - DDC Series 60 Engine

Test Number: 06R0772310-1

Test Procedure: 210 hr Tactical Wheeled Vehicle

EVALUATION OF OIL MANAGEMENT SYSTEMS (OMS)

Work Directive No. 39

HTV - DDC Series 60 Engine

OMS Equipment: ASTI Oil Sensor
Test Lubricant: AL-27170-L
Army Reference Oil, MIL-PRF-2104G, SAE 15W40
Test Fuel: JP8
Test Number: 06RO772310-1
Start of Test Date: February 22, 2006
End of Test Date: March 28, 2006
Test Duration: 210 Hours
Test Procedure: 210 hr Tactical Wheeled Vehicle

Conducted for

U.S. Army RDECOM
Tank-Automotive Research, Development & Engineering Center
Petroleum and Water Business Area
Warren, Michigan 48397-5000

Contents

Introduction

This test was conducted at Southwest Research Institute (SwRI) in support of work directive number 39 – Evaluation of Oil Management Systems (OMS). The purpose of this particular test was to establish a baseline of engine lubricant performance in a HTV - DDC Series 60 Engine utilizing a modified version of the 210 hr Tactical Wheeled Vehicle test procedure.

Test Engine

The test engine was a HTV – Detroit Diesel Corporation Series 60 engine equipped with air compressor and Jake Brake assembly. The Jake Brake assembly was physically installed but was electrically de-activated for this test. The engine was equipped with an ASTI oil quality monitoring system. The engine was disassembled, measured for pre-test wear measurements, clearances and specifications verified, and re-assembled following the guidelines in the service manual.

Test Stand Configuration

The engine was coupled to a suitable dynamometer capable of absorbing the required load. External liquid-to-liquid heat exchangers were utilized for control of oil sump temperature and coolant temperature. Boost air temperature was controlled using a liquid to air heat exchanger.

Engine Run-in

Before beginning the test cycle, the engine was equipped with new oil filters and filled with a fresh oil charge of 38 quarts and ran-in using the following schedule.

Duration	Ends when Water Jacket Outlet > 169 °F	5 minutes	10 minutes	12 minutes
Speed, rpm	1500 ± 25	1500 ± 10	1750 ± 10	2100 ± 10
Torque, ft-lb	Minimum	800 ± 25	1075 ± 25	Full Load
Coolant Out, °F	170	205 ± 3	205 ± 3	205 ± 3
Oil Sump, °F	255 Maximum	255 Maximum	255 Maximum	255 Maximum

Pre-test Engine Performance Checks

At the completion of the run-in, new oil filters were installed and a fresh oil charge of 38 quarts was added to the oil sump. A full load power curve was conducted starting at 900 rpm and ending at 2100 rpm using 100 rpm steps.

Test Cycle

The standard 210 hr Tactical Wheeled Vehicle Cycle was modified to provide for 20 hours of continuous running followed by a 4-hour soak. The first 18 hours of each 20-hour running segment was composed of 6 cycles of 3 hour of continuous operation. Each cycle consisted of 2 hours of operation at rated speed and full power conditions followed by a 1 hour of operation at idle conditions. The last 2 hours of each 20-hour running segment was composed of 2 hours at rated speed and full power conditions. Test time was accumulated only during the running segment.
Test coolant was a 60/40 blend of Prestone II antifreeze and de-ionized water. Test oil was AL-27170-L Army Reference Oil, MIL-PRF-2104G, SAE 15W40 grade. Test fuel was JP-8. Coolant and oil temperatures were elevated to simulate desert warfare conditions but limited to a Maximum oil sump temperature of 260°f.

Test Cycle Operational Targets

Parameter	Rated Speed / Full Power	Idle
Duration, min.	120	60
Engine Speed, rpm	2100 ± 25	900 ± 25
Water Jacket Outlet, ° F	215 ± 3	110 ± 3
Oil Sump, °F	255 ± 3	110 ± 3[1]

Oil Level Checks

Every 20 hours of operation the engine was stopped and allowed to soak for 4 hours. The oil level was checked and recorded at 20 minutes into the soak period. Fresh oil was then added to restore the oil level to the full mark.

Oil Sampling

Oil samples were obtained every 14 hours of test operation. At 70, 140, and 210 hours 16 fluid ounce samples were retained. After obtaining the 70 and 140 hour sample, 16 fluid ounces of fresh oil were added to the sump. For all other sample times, an 8 fluid ounce sample was retained followed by 8 ounces of fresh oil added to the sump.

Post-test Engine Performance Checks

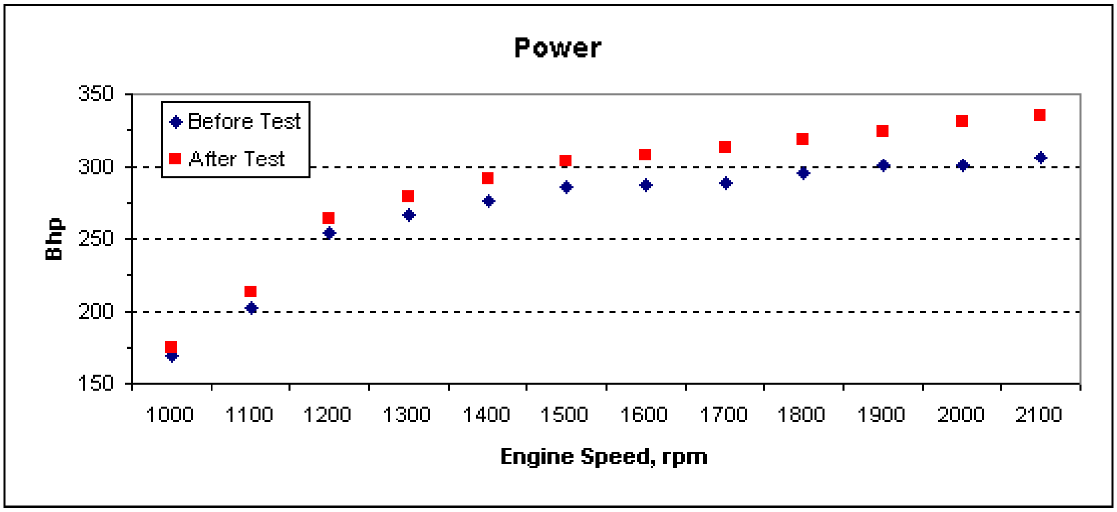
At the completion of the 210-hour test, a full load power curve was conducted starting at 900 rpm and ending at 2100 rpm using 100 rpm steps.

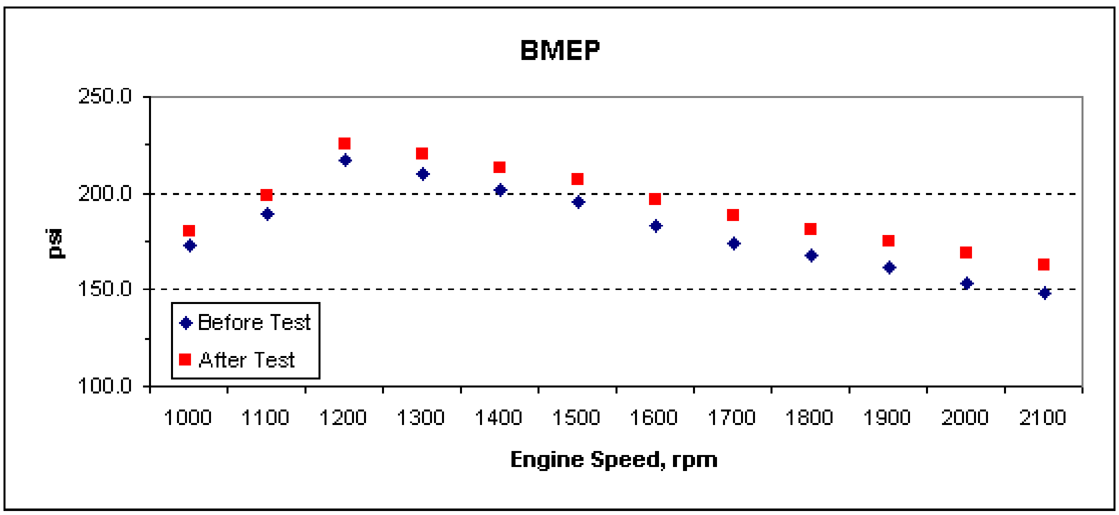
[1] Thermal loading in conjunction with oil sump capacity of 38 quarts and low oil flow at idle prevented reaching the target oil temperature during idle.

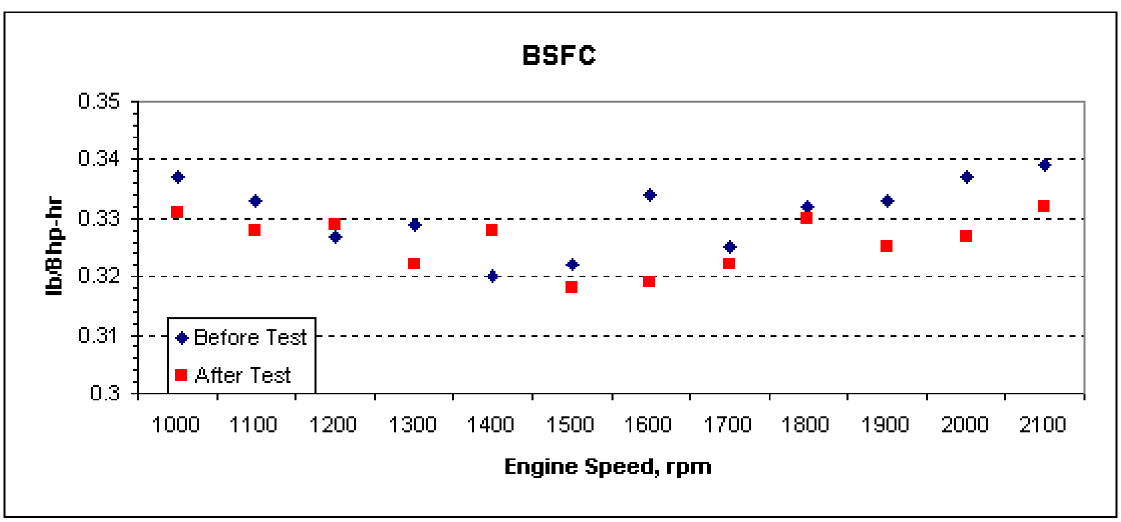
Engine Operating Conditions Summary

	Maximum Power Mode (2100 rpm)		Idle Mode	
	Mean	Standard Deviation	Mean	Standard Deviation
Engine Speed, rpm	2102	1.7	900	0.5
Torque, ft-lb	843.8	9.3	66.5	1.9
Fuel Consumption, lb/hr	113.4	2.2	9.7	0.3
Observed Power, Bhp	337.7	3.9	11.5	0.5
BSFC, lb/BHP-hr	0.336	0.007	0.850	0.053
Temperatures, °F				
Exhaust Cyls. 1-3 Before Turbo	1008.1	11.8	273.7	9.4
Exhaust Cyls. 4-6 Before Turbo	1032.5	13.2	265.0	3.9
Exhaust After Turbo	840.2	12.6	256.6	5.2
Water Jacket Inlet	207.5	0.7	105.2	0.3
Water Jacket Outlet	215.0	0.6	110.0	0.2
Oil Sump	254.7	3.2	138.5	0.8
Fuel at Filter	121.0	1.8	80.4	4.0
Inlet Air	125.0	0.3	76.2	5.8
Airbox	74.9	7.6	68.7	5.8
Exhaust Port Cylinder 1	969.9	12.4	246.7	18.6
Exhaust Port Cylinder 2	943.3	11.3	255.5	10.9
Exhaust Port Cylinder 3	936.6	10.0	267.2	13.0
Exhaust Port Cylinder 4	940.3	13.0	255.1	11.4
Exhaust Port Cylinder 5	1004.7	12.8	257.5	13.2
Exhaust Port Cylinder 6	954.0	12.1	241.5	13.6
Pressures				
Exhaust Before Turbo, psi	7.7	5.8	0.4	0.2
Exhaust After Turbo, psi	2.0	0.1	0.1	0.1
Compressor Discharge, psi	15.3	0.4	0.4	0.0
Oil Gallery, psi	53.0	0.9	55.1	0.3
Intake Pressure, psiA	29.6	0.4	14.8	0.1
Barometric Pressure, psiA	14.4	0.1	14.4	0.1
Intake Pressure, psi	15.3	0.4	0.4	0.0

Performance Curves







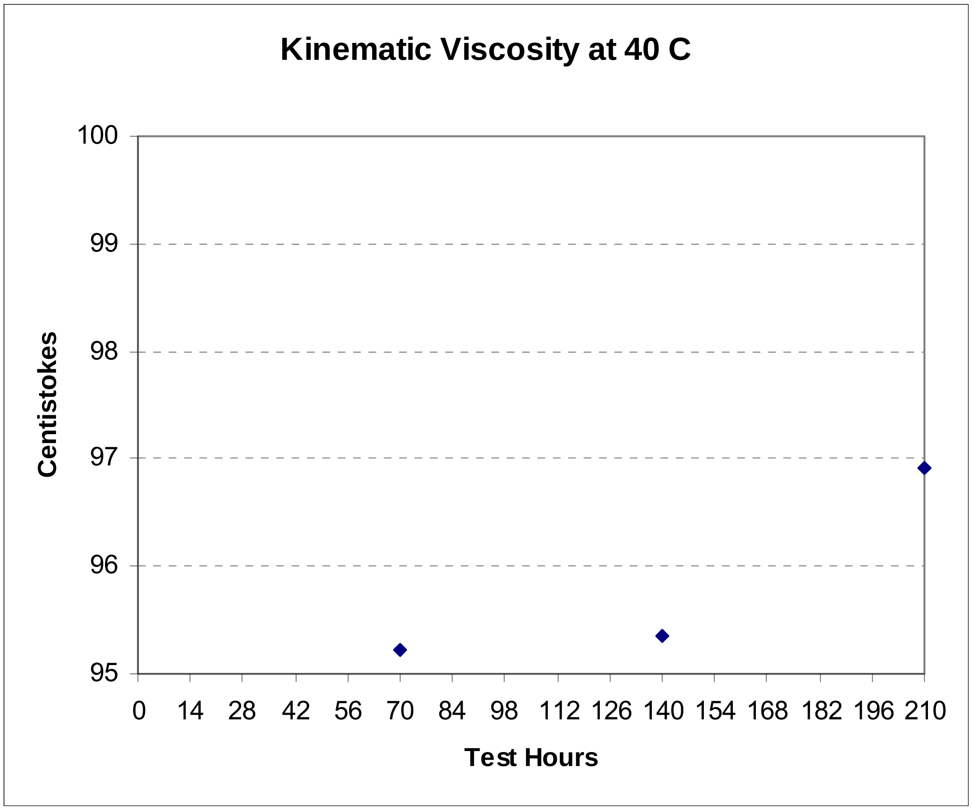
Emissions Data

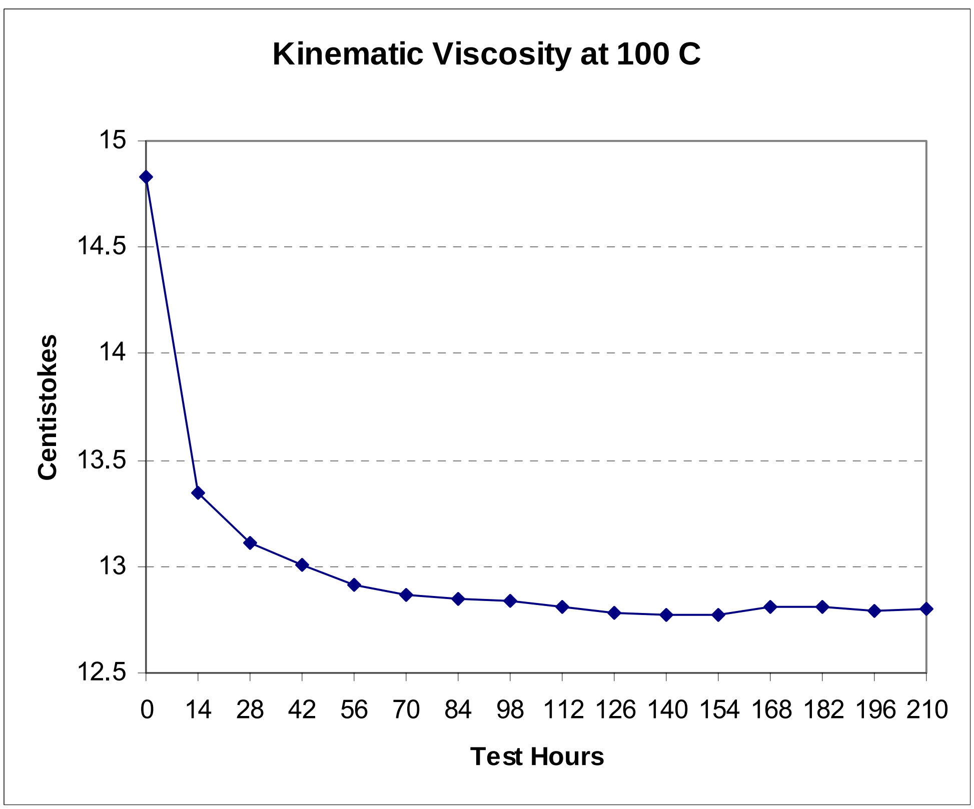
Test Hours	Smoke, % opacity	NOx, ppm	02, %	CO2, %	CO, ppm	HC, ppm
1	0.3	1230	11.43	6.86	83	0
21	0.4	1129	11.1	7.1	104	160
41	0.5	1258	11.24	6.99	88	50
61	0.3	1140	11.05	7.14	103	40
81	0.3	1101	10.86	7.27	121	80
101	0.4	1313	11.05	7.13	99	50
121	0.5	1320	11.13	7.02	90	60
141	0.4	1296	11.31	6.95	87	0
161	0.3	1309	11.36	6.91	77	70
181	0.5	1301	11.3	6.95	79	30
201	0.4	1306	11.25	6.99	86	80
Minimum	0.3	1101	10.86	6.86	77	0
Maximum	0.5	1320	11.43	7.27	121	160
Average	0.4	1245.7	11.2	7	92.5	56.4
Standard Deviation	0.08	83.31	0.17	0.12	13.07	44.11

New and Used Lubricant Analysis

Test Hours	0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210
Total Base Number, mg KOH/g (ASTM D 4739)	8.1	7.46	7.09	6.94	6.51	6.1	6.29	5.52	5.38	5.34	5.44	5.31	4.81	4.73	4.59	4.46
Total Acid Number, mg KOH/g (ASTM D 664)	1.9	2.01	1.94	2.14	2.23	2.19	2.24	2.19	2.21	2.26	2.28	2.42	2.31	2.28	2.35	2.27
Kinematic Viscosity at 100°C, cst (ASTM D 445)	14.83	13.35	13.11	13.01	12.91	12.87	12.85	12.84	12.81	12.78	12.77	12.77	12.81	12.81	12.79	12.8
Kinematic Viscosity at 40°C, cst (ASTM D 445)		---	---	---	---	95.23	---	---	---	---	95.36	---	---	---	---	96.92
VI Index (ASTM D 2270)		---	---	---	---	132	---	---	---	---	130	---	---	---	---	128
API Gravity (ASTM D 4052)	28.2	28	28	28	27.9	27.8	27.8	27.8	27.7	27.7	27.8	27.9	27.8	27.7	27.7	27.7
Density (ASTM D 4052)		0.8863	0.8861	0.8864	0.8867	0.8871	0.8873	0.8875	0.8877	0.8877	0.8872	0.8869	0.8872	0.8881	0.8882	0.8877
Soot (TGA)		0.379	0.272	0.228	0.297	0.23	0.192	0.137	0.276	0.283	0.205	0.413	0.491	0.35	0.414	0.388
Oxidation, Abs./cm (ASTM E 168)		0.25	0.32	0.55	0.83	1.11	1.35	1.79	1.95	2.27	2.62	2.91	3.12	3.51	3.78	4.04
Nitration, Abs./cm (ASTM E 168)		0.09	0.09	0.09	0.09	0.09	0	0	0	0	0	0	0	0	0	0
Wear Metals by ICP, ppm (ASTM D 5185)																
Fe	2	5	7	8	10	11	12	14	14	15	16	16	17	18	19	20
Cu	<1	3	5	8	9	10	11	13	14	14	15	14	15	15	15	15
Al	<1	<1	1	1	1	1	1	1	1	1	1	<1	1	1	1	1
Si	4	4	6	5	6	5	6	7	6	8	6	6	8	7	7	7
Ag	<1	<1	<1	13	27	<1	<1	1	<1	<1	<1	1	<1	5	2	1
Sn	<1	1	2	3	3	4	4	4	4	5	5	5	5	5	5	5
Pb	<1	1	2	3	3	3	4	4	4	4	5	5	5	6	5	5

New and Used Oil Analysis Trends





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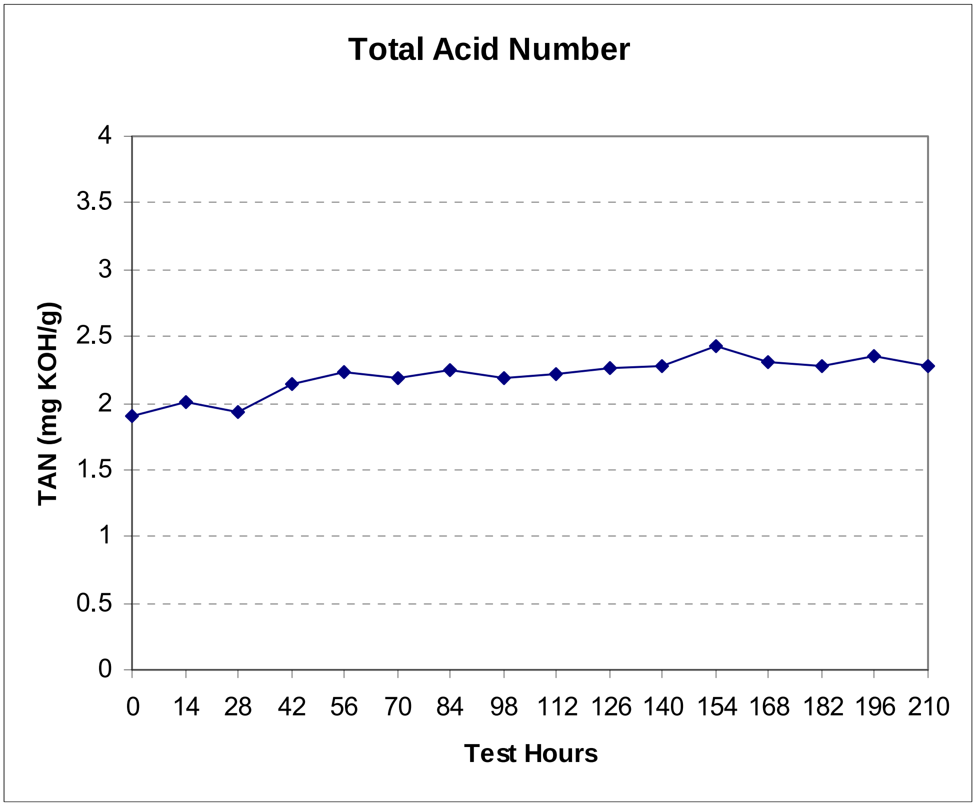
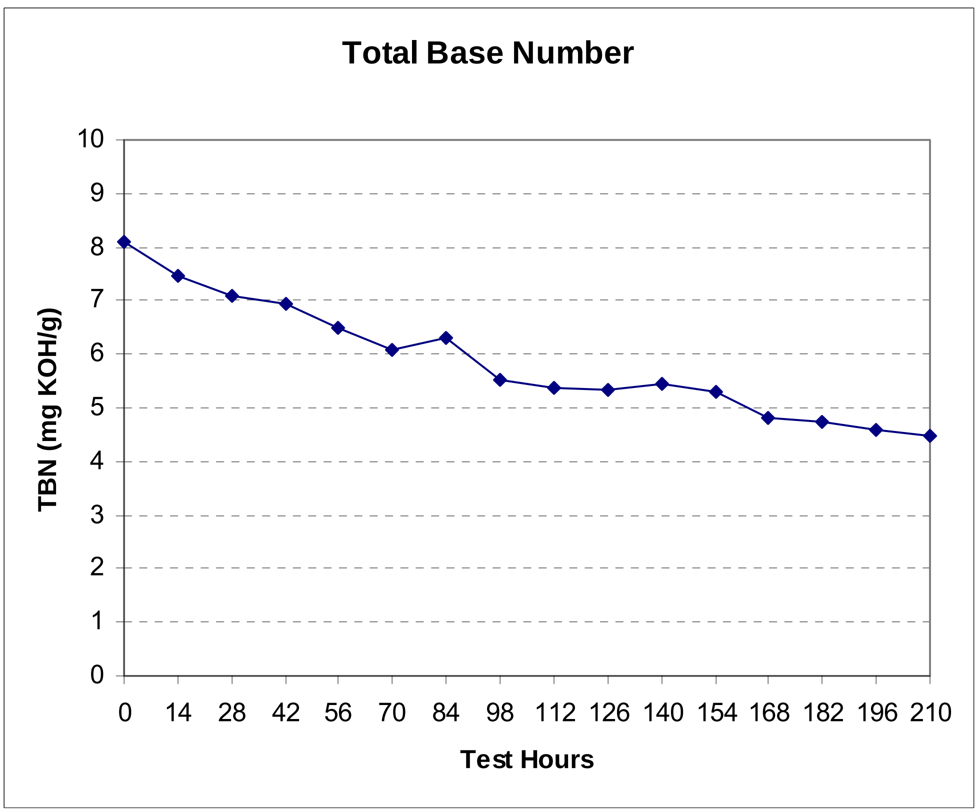
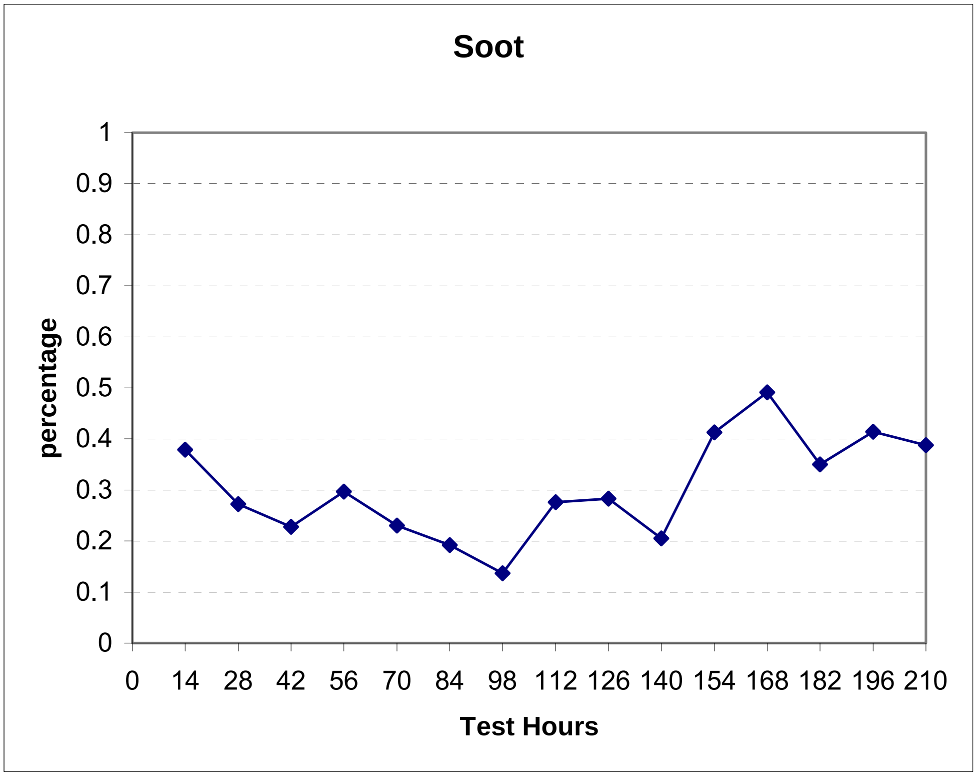
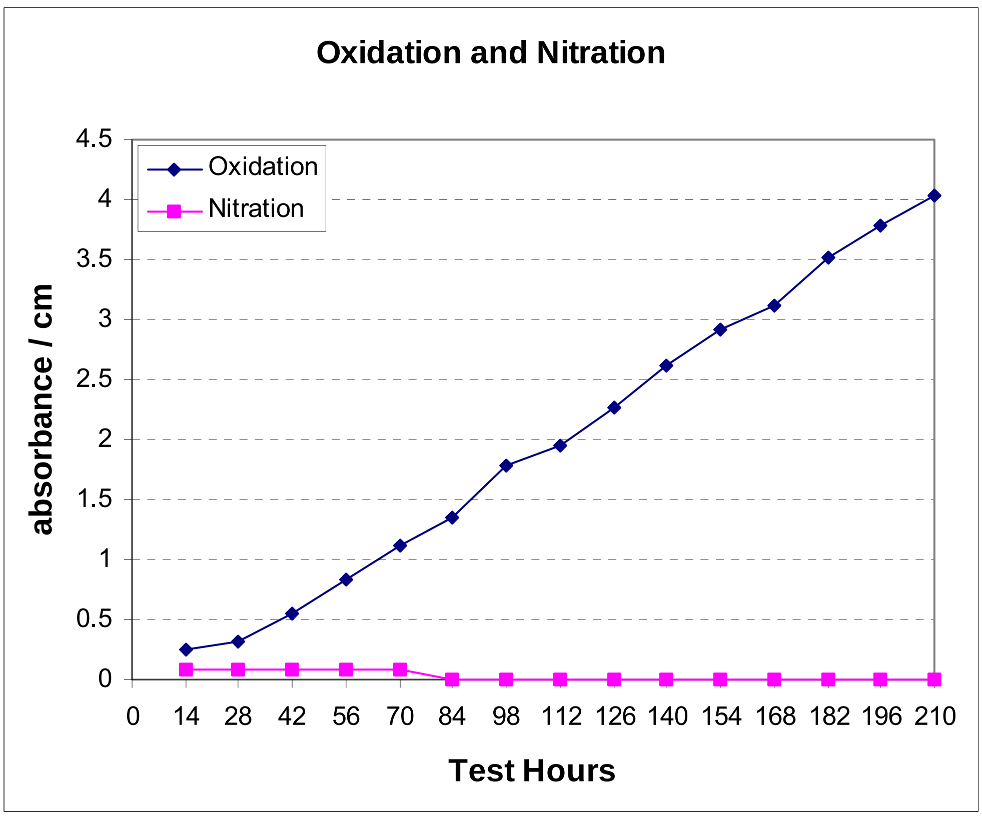


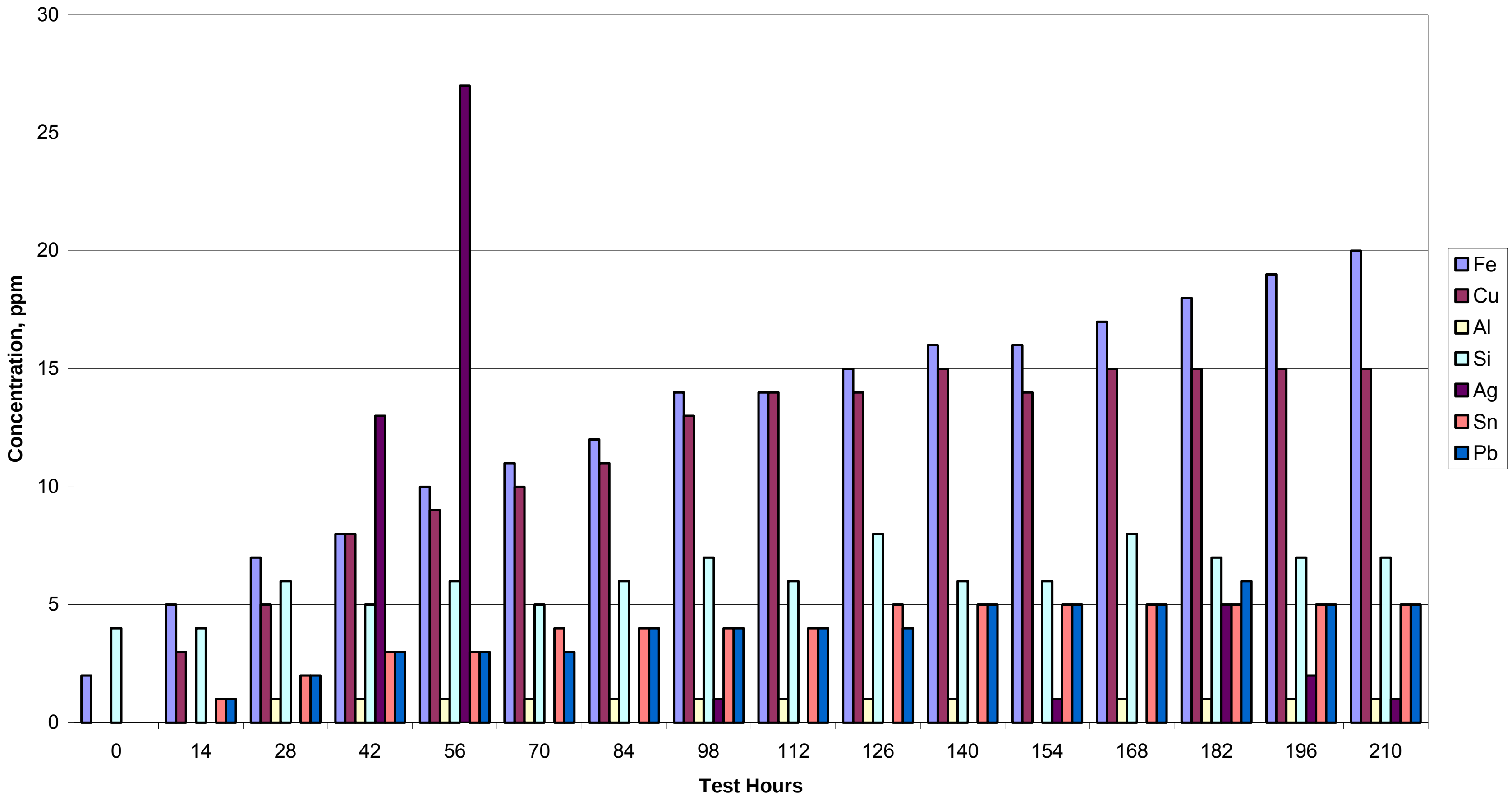


New and Used Oil Analysis Trends





New and Used Oil Wear Metal Trends



Oil Consumption Data

Test time, hours	Oil Consumed , lbs	Cumulative Oil Consumed, lbs
20	0	0
40	0	0
60	0	0
80	0	0
100	0	0
120	1.35	1.35
140	0.91	2.26
160	1.82	4.08
180	0.92	5.00
200	1.26	6.26
210	0.14	6.40

Cumulative oil consumed for the entire 210-hour test was 6.40 lbs.

Average hourly oil consumption for 210 hours of test was 0.030 lbs per hour.

Post Test Engine Condition and Deposits

Evaluation	Cylinder Number						
	1	2	3	4	5	6	Average
Piston Ring Sticking							
No. 1	None	None	None	None	None	None	None
No. 2	None	None	None	None	None	None	None
No. 3	None	None	None	None	None	None	None
Scuffing, % Area							
No. 1 Ring	0	0	0	0	0	0	0
No. 2 Ring	0	0	0	0	0	0	0
No. 3 Ring	0	0	0	0	0	0	0
Piston Crown	0	0	0	0	0	0	0
Piston Skirt	0	0	0	0	0	0	0
Cylinder Liner	0	0	0	0	0	0	0
Piston Carbon Rating, Demerits							
No. 1 Groove	60.00	40.25	37.75	39.75	41.25	26.50	40.92
No. 2 Groove	1.25	---	1.75	---	---	---	1.50
No. 3 Groove	---	---	---	---	---	---	---
No. 1 Land	27.25	36.25	34.00	34.75	31.00	26.50	31.63
No. 2 Land	19.25	5.00	14.50	19.75	15.00	17.75	15.21
No. 3 Land	---	---	---	---	---	---	---
No. 4 Land	---	---	---	---	---	---	---
Cooling Gallery	---	---	---	---	---	---	---
Undercrown	---	---	---	---	---	---	---
Piston Lacquer Rating, Demerits							
No. 1 Groove	---	---	---	---	---	---	---
No. 2 Groove	5.33	3.24	2.94	6.13	3.54	3.32	4.08
No. 3 Groove	5.19	3.90	2.85	4.20	1.10	1.50	3.12
No. 1 Land	---	---	---	---	---	---	---
No. 2 Land	1.52	3.10	2.23	0.53	2.08	1.55	1.84
No. 3 Land	4.20	2.10	1.64	2.24	1.50	1.50	2.20
No. 4 Land	4.20	1.50	1.50	1.50	1.50	1.50	1.95
Cooling Gallery	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Undercrown	3.90	2.24	2.10	1.50	1.50	1.50	2.12
Total Demerits	133.6	99.1	102.8	111.9	100	83.1	105.1
Miscellaneous							
Top Groove Fill, %	55	20	22	29	40	20	31
Intermediate Groove Fill, %	0	0	0	0	0	0	0
Top Land Heavy Carbon, %	3	15	12	13	8	2	8.8
Top Land Flaked Cabon, %	3	0	0	0	0	0	0.5
Exhaust Valve Tulip Deposits, merits							
Front	8.3	8.3	8.1	8.3	8.6	9.0	8.4
Rear	8.5	8.4	8.5	8.4	8.6	9.0	8.6
Intake Valve Tulip Deposits, merits							
Front	8.5	8.8	9.5	9.5	9.9	9.9	9.4
Rear	9.2	9.0	9.2	9.7	9.3	9.0	9.2

Engine Rebuild Measurements, inches

	Minimum	Maximum	Average	Specified Limits
Cylinder Liners (Installed)				
Inside Diameter	5.119	5.1195	5.1194	5.118 to 5.120
Out of Round	0.0000	0.0013	0.0004	0.001 max
Taper	0.0002	0.0013	0.0007	
Piston Skirt Diameter	5.1122	5.1136	5.1128	
Piston Skirt to Cylinder Liner Clearance	0.0057	0.0073	0.0065	0.002 to 0.0072
Piston Ring End Gaps				
Top Ring	0.027	0.029	0.028	
Second Ring	0.036	0.039	0.037	
Oil Control Ring	0.017	0.020	0.020	
Ring to Groove Clearances				
Oil Control Ring	0.001	0.001	0.001	0.001 to 0.004
Piston Pin				
Piston Pin Diameter	1.7713	1.7714	1.7714	1.7712 to 1.7716
Pin Bore in Dome	1.7744	1.7748	1.7746	1.7728 to 1.7740
Bearing Clearances				
Connecting Rod Bearing to Journal	0.002	0.002	0.002	0.0016 to 0.0056
Main Bearing to Journal	0.003	0.003	0.003	0.0016 to 0.005
Camshaft Bearing to Journal	0.005	0.005	0.005	0.0035 to 0.0065

Cylinder Liner Bore Diameter Changes, inches

Cylinder	Depth	T-AT	F-B	Individual Cylinder Average Change
1	Top	0.0002	-0.0004	
	Middle	0.0003	0.0000	0.0001
	Bottom	0.0002	0.0000	
2	Top	0.0000	-0.0007	
	Middle	-0.0001	-0.0001	-0.0001
	Bottom	0.0001	0.0000	
3	Top	0.0006	0.0000	
	Middle	0.0000	-0.0002	0.0001
	Bottom	0.0000	-0.0001	
4	Top	0.0006	-0.0008	
	Middle	-0.0004	-0.0005	-0.0002
	Bottom	-0.0002	0.0000	
5	Top	0.0003	-0.0006	
	Middle	-0.0001	-0.0004	-0.0002
	Bottom	-0.0001	-0.0002	
6	Top	0.0005	-0.0006	
	Middle	0.0000	-0.0003	-0.0001
	Bottom	0.0000	-0.0002	
Average Change for All Cylinders	Top	0.0004	-0.0005	
	Middle	0.0000	-0.0003	
	Bottom	0.0000	-0.0001	

Overall Average change: -0.0001

Cylinder Liner Wear By PDI Surface Analysis, µm

Cylinder	Front	Thrust	Back	Anti-thrust
1	2.469	3.417	3.018	3.231
2	2.989	3.308	3.319	2.463
3	3.694	3.538	2.743	3.118
4	3.34	2.83	2.627	2.874
5	3.538	2.993	2.64	2.768
6	3.455	3.144	3.039	3.139

Maximum Cylinder Liner Wear	3.694
Average Cylinder Liner Wear	3.071

Top Ring Radial Wear, inches

Cylinder Number	Position	Before	After	Delta
1	1	0.2033	0.2025	0.0008
	2	0.1983	0.1983	0.0000
	3	0.1998	0.1936	0.0062
	4	0.2000	0.1998	0.0002
	5	0.2035	0.2023	0.0012
2	1	0.2032	0.2016	0.0016
	2	0.1991	0.1990	0.0001
	3	0.2003	0.2003	0.0000
	4	0.2007	0.2007	0.0000
	5	0.2019	0.2017	0.0002
3	1	0.2036	0.2025	0.0011
	2	0.1993	0.1991	0.0002
	3	0.1989	0.1986	0.0003
	4	0.1995	0.1993	0.0002
	5	0.2013	0.2002	0.0011
4	1	0.2007	0.1995	0.0012
	2	0.1996	0.1996	0.0000
	3	0.1996	0.1996	0.0000
	4	0.1987	0.1987	0.0000
	5	0.2003	0.2003	0.0000
5	1	0.2009	0.1989	0.0020
	2	0.1976	0.1976	0.0000
	3	0.1979	0.1974	0.0005
	4	0.1959	0.1958	0.0001
	5	0.1986	0.1986	0.0000
6	1	0.2016	0.2008	0.0008
	2	0.1986	0.1986	0.0000
	3	0.1997	0.1996	0.0001
	4	0.2000	0.2000	0.0000
	5	0.2009	0.2009	0.0000

Maximum	0.0062
Average	0.0006

Piston Ring Gap Measurements, inches

Cylinder Number	Ring No.	Before	After	Delta
1	1	0.028	0.028	0.000
	2	0.036	0.037	0.001
	3	0.020	0.021	0.001
2	1	0.027	0.027	0.000
	2	0.039	0.039	0.000
	3	0.020	0.020	0.000
3	1	0.028	0.028	0.000
	2	0.038	0.039	0.001
	3	0.017	0.018	0.001
4	1	0.027	0.028	0.001
	2	0.037	0.038	0.001
	3	0.020	0.021	0.001
5	1	0.029	0.029	0.000
	2	0.036	0.037	0.001
	3	0.020	0.021	0.001
6	1	0.029	0.029	0.000
	2	0.037	0.038	0.001
	3	0.020	0.020	0.000

Ring No. 1, Maximum	0.001
Ring No. 2, Maximum	0.001
Ring No. 3, Maximum	0.001

Ring No. 1, Average	0.0002
Ring No. 2, Average	0.0008
Ring No. 3, Average	0.0004

Piston Ring Mass, grams

Cylinder Number	Ring No.	Before	After	Delta
1	1	42.9234	42.9155	0.0079
	2	41.9923	41.9870	0.0053
	3	29.1557	29.1539	0.0018
2	1	43.1861	43.1794	0.0067
	2	42.0336	42.0334	0.0002
	3	29.2653	29.2653	0.0000
3	1	42.8774	42.8675	0.0099
	2	42.1183	42.1182	0.0001
	3	29.2793	29.2770	0.0023
4	1	42.8635	42.8529	0.0106
	2	41.9905	41.9898	0.0007
	3	29.2243	29.2222	0.0021
5	1	42.4904	42.4812	0.0092
	2	42.0001	42.0001	0.0000
	3	29.5242	29.5212	0.0030
6	1	42.9254	42.9099	0.0155
	2	42.1448	42.1438	0.0010
	3	29.4020	29.3987	0.0033

Ring No. 1, Maximum	0.0155
Ring No. 2, Maximum	0.0053
Ring No. 3, Maximum	0.0033

Ring No. 1, Average	0.0100
Ring No. 2, Average	0.0012
Ring No. 3, Average	0.0032

Top Piston Ring Width, inches

Cylinder Number	Before	After	Delta
1	0.1312	0.1312	0.0000
2	0.1348	0.1346	0.0002
3	0.1318	0.1317	0.0001
4	0.1320	0.1320	0.0000
5	0.1321	0.1316	0.0005
6	0.1325	0.1324	0.0001

Maximum	0.0005
Average	0.0002

Top Piston Ring Plating Thickness, inches

Cylinder Number	Position	Before	After	Delta
1	1	0.01395	0.01355	0.00040
	2	0.01255	0.01245	0.00010
	3	0.01355	0.01355	0.00000
	4	0.01375	0.01350	0.00025
	5	0.01395	0.01355	0.00040
2	1	0.01325	0.01295	0.00030
	2	0.01160	0.01125	0.00035
	3	0.01240	0.01220	0.00020
	4	0.01235	0.01235	0.00000
	5	0.01300	0.01295	0.00005
3	1	0.01430	0.01420	0.00010
	2	0.01290	0.01275	0.00015
	3	0.01195	0.01190	0.00005
	4	0.01300	0.01295	0.00005
	5	0.01370	0.01370	0.00000
4	1	0.01275	0.01265	0.00010
	2	0.01240	0.01210	0.00030
	3	0.01350	0.01350	0.00000
	4	0.01275	0.01245	0.00030
	5	0.01290	0.01285	0.00005
5	1	0.01270	0.01240	0.00030
	2	0.01060	0.01060	0.00000
	3	0.01110	0.01100	0.00010
	4	0.01090	0.01090	0.00000
	5	0.01145	0.01140	0.00005
6	1	0.01330	0.01320	0.00010
	2	0.01140	0.01140	0.00000
	3	0.01330	0.01325	0.00005
	4	0.01305	0.01305	0.00000
	5	0.01295	0.01290	0.00005

Maximum	0.00040
Average	0.00013

Slipper Bushing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1	153.9872	153.9084	0.0788
2	152.7380	152.6327	0.1053
3	153.7068	153.6493	0.0575
4	152.5638	152.4963	0.0675
5	153.3161	153.2580	0.0581
6	153.1481	153.0648	0.0833

Maximum	0.1053
Average	0.0751

Camshaft Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	53.8243	53.8237	0.0006
1B	54.2362	54.2349	0.0013
2T	53.8359	53.8356	0.0003
2B	54.5177	54.5156	0.0021
3T	53.8311	53.8311	0.0000
3B	54.3320	54.3316	0.0004
4T	53.8221	53.8218	0.0003
4B	54.5156	54.5146	0.0010
5T	53.7981	53.7977	0.0004
5B	54.5869	54.5859	0.0010
6T	53.7819	53.7815	0.0004
6B	54.5110	54.5087	0.0023
7T	53.9387	53.9345	0.0042
7B	54.4290	54.4283	0.0007

Maximum	0.0042
Average	0.0011

Connecting Rod Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	157.9024	157.8811	0.0213
1B	153.0301	153.0177	0.0124
2T	158.0973	158.0433	0.0540
2B	152.9606	152.9339	0.0267
3T	158.0758	158.0262	0.0496
3B	153.0318	153.0106	0.0212
4T	158.0923	158.0616	0.0307
4B	153.2686	153.2524	0.0162
5T	158.1355	158.0751	0.0604
5B	153.2511	153.2070	0.0441
6T	157.6702	157.6397	0.0305
6B	153.1854	153.1732	0.0122

Maximum	0.0604
Average	0.0316

Main Bearing Weight Loss, grams

Cylinder Number	Pre-test	Post-test	Weight Loss
1T	223.7036	223.6901	0.0135
1B	248.5258	248.5140	0.0118
2T	222.0330	222.0256	0.0074
2B	248.2626	248.2380	0.0246
3T	223.7425	223.7392	0.0033
3B	248.4335	248.3080	0.1255
4T	221.8932	221.8902	0.0030
4B	248.6720	248.6542	0.0178
5T	223.9444	223.9380	0.0064
5B	248.2021	248.1778	0.0243
6T	246.0854	246.0730	0.0124
6B	248.5384	248.5118	0.0266
7T	222.2251	222.2139	0.0112
7B	248.3313	248.3213	0.0100

Maximum	0.1255
Average	0.0213

Before Test Cylinder Liner Measurements, inches

Cyl.	Depth	Transverse (TD)	Longitude (LD)	Average Bore Diameter	Out of Round
1	Top	5.1183	5.1193		0.0010
	Middle	5.1189	5.1191	5.1190	0.0002
	Bottom	5.1191	5.1191		0.0000
	Taper	0.0008	0.0002		
2	Top	5.1188	5.1193		0.0005
	Middle	5.1194	5.1191	5.1194	0.0003
	Bottom	5.1194	5.1191		0.0003
	Taper	0.0006	0.0002		
3	Top	5.1183	5.1188		0.0005
	Middle	5.1194	5.1192	5.1195	0.0002
	Bottom	5.1196	5.1192		0.0004
	Taper	0.0013	0.0004		
4	Top	5.1183	5.1196		0.0013
	Middle	5.1194	5.1195	5.1195	0.0001
	Bottom	5.1196	5.1190		0.0006
	Taper	0.0013	0.0006		
5	Top	5.1185	5.1194		0.0009
	Middle	5.1193	5.1194	5.1194	0.0001
	Bottom	5.1194	5.1191		0.0003
	Taper	0.0009	0.0003		
6	Top	5.1184	5.1194		0.0010
	Middle	5.1193	5.1194	5.1194	0.0001
	Bottom	5.1194	5.1191		0.0003
	Taper	0.0010	0.0003		

Average Bore Diameter = (TD@MID + TD@BOT)/2

Piston Skirt to Cylinder Liner Clearance, inches

Cylinder	Average Bore Diameter	Piston Skirt Diameter	Clearance
1	5.1190	5.1125	0.0065
2	5.1194	5.1128	0.0066
3	5.1195	5.1122	0.0073
4	5.1195	5.1123	0.0072
5	5.1194	5.1135	0.0058
6	5.1194	5.1136	0.0057

Specifications
- Cylinder Liner Installed Inside Diameter 5.118" to 5.120"
- Cylinder Liner Maximum Out of Round 0.001"
- Piston Skirt to Cylinder Liner Clearance 0.002" to 0.0072"

After Test Cylinder Liner Measurements, inches

Cyl.	Depth	Transverse (TD)	Longitude (LD)	Average Bore Diameter	Out of Round
1	Top	5.1185	5.1189		0.0004
	Middle	5.1192	5.1191	5.1193	0.0001
	Bottom	5.1193	5.1191		0.0002
	Taper	0.0008	0.0002		
2	Top	5.1188	5.1186		0.0002
	Middle	5.1193	5.1190	5.1194	0.0003
	Bottom	5.1195	5.1191		0.0004
	Taper	0.0007	0.0005		
3	Top	5.1189	5.1188		0.0001
	Middle	5.1194	5.1190	5.1195	0.0004
	Bottom	5.1196	5.1191		0.0005
	Taper	0.0007	0.0003		
4	Top	5.1189	5.1188		0.0001
	Middle	5.1190	5.1190	5.1192	0.0000
	Bottom	5.1194	5.1190		0.0004
	Taper	0.0005	0.0002		
5	Top	5.1188	5.1188		0.0000
	Middle	5.1192	5.1190	5.1193	0.0002
	Bottom	5.1193	5.1189		0.0004
	Taper	0.0005	0.0002		
6	Top	5.1189	5.1188		0.0001
	Middle	5.1193	5.1191	5.1194	0.0002
	Bottom	5.1194	5.1189		0.0005
	Taper	0.0005	0.0003		

Average Bore Diameter = (TD@MID + TD@BOT)/2

Photographs

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27170L	**EOT Date:**	20060328
Test No.:	06R0772310-1	**Test Length:**	210

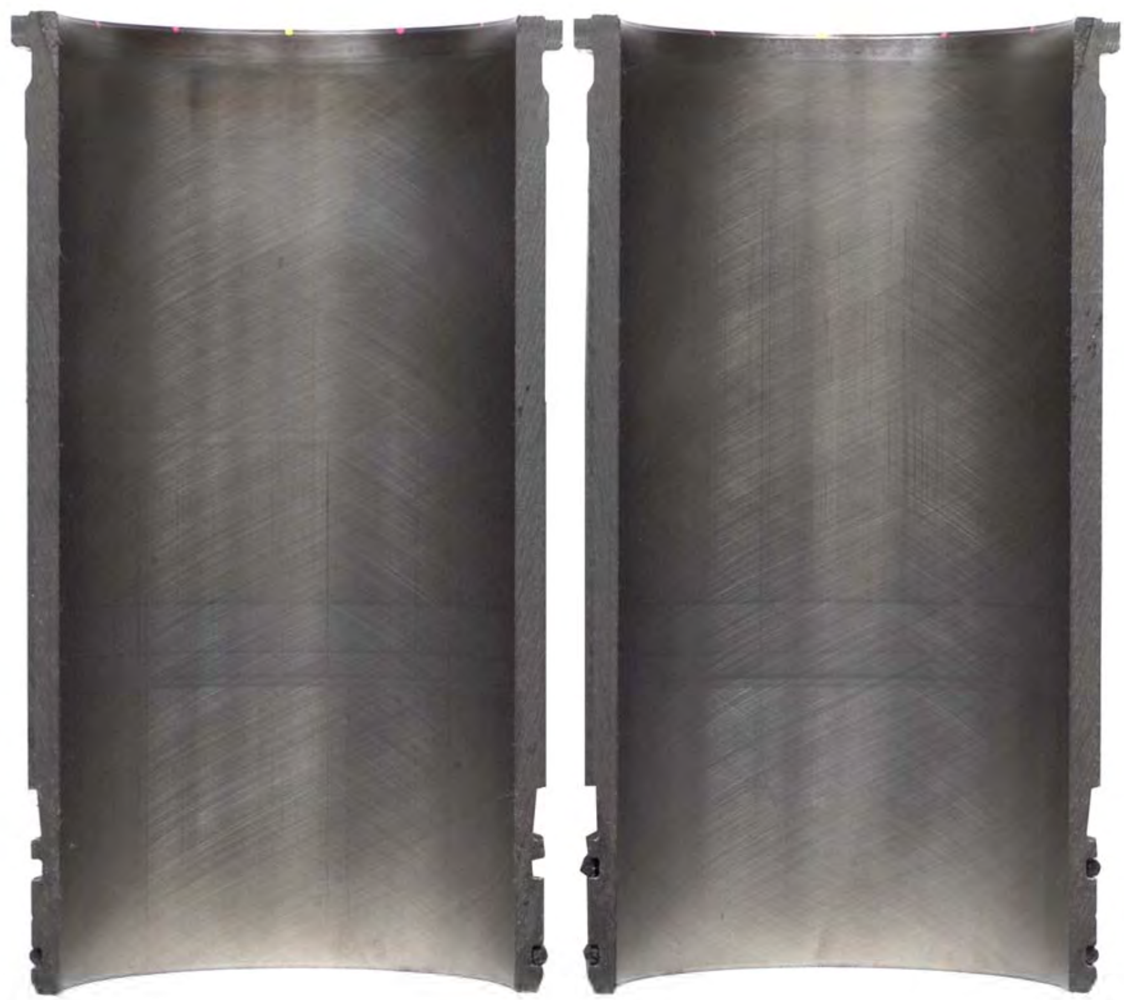
Piston Skirt Thrust - Best **Cyl. 6**

Piston Skirt Anti-thrust - Best **Cyl. 6**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27170L	**EOT Date:**	20060328
Test No.:	06R0772310-1	**Test Length:**	210

Cylinder Sleeves Thrust / Anti-thrust - Worst **Cyl. 1**



Oil Code:	AL-27170L	**EOT Date:**	20060328
Test No.:	06R0772310-1	**Test Length:**	210

Exhaust and Intake Valve - Worst Cyl. 1

Oil Code:	AL-27170L	EOT Date:	20060328
Test No.:	06R0772310-1	Test Length:	210

Main Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Exhaust and Intake Valve - Worst Cyl. 5

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Exhaust and Intake Valve - Best **Cyl. 2**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Cylinder Sleeves Thrust / Anti-thrust - Worst **Cyl. 1**

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27170L	**EOT Date:**	20060328
Test No.:	06R0772310-1	**Test Length:**	210

Rod Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

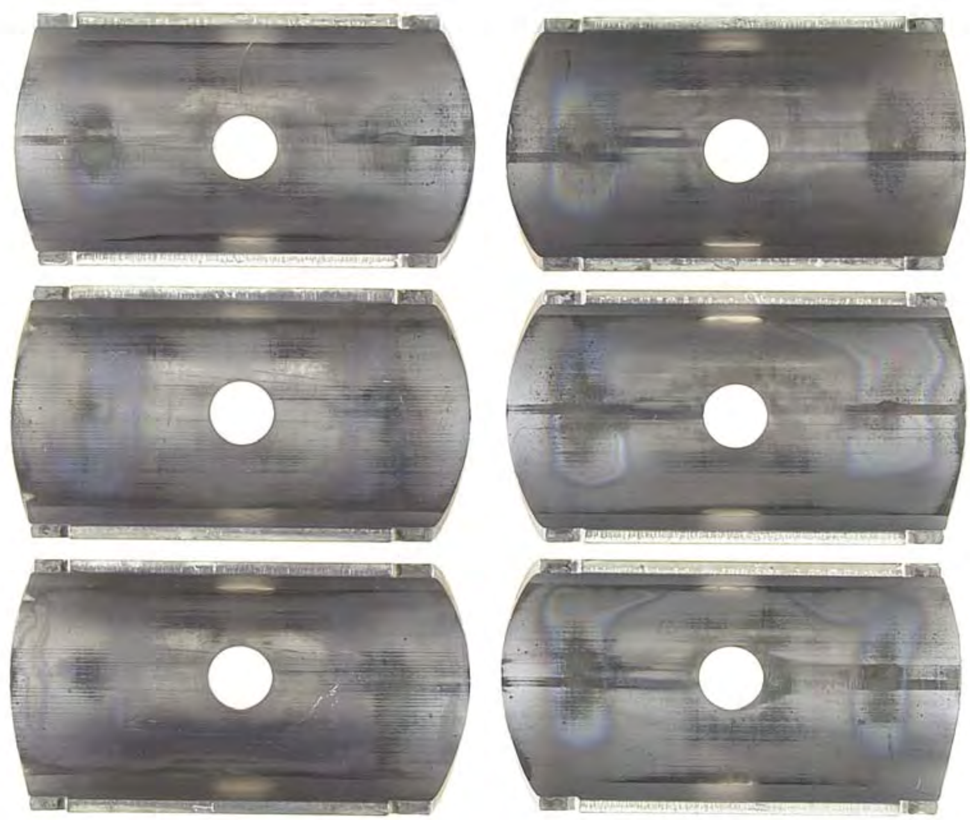
Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Camshaft Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Slipper Bushings



Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Main Bearings

Detroit Diesel Series 60 - Tactical Wheeled Vehicle Cycle

Oil Code:	AL-27015-L	**EOT Date:**	10/18/06
Test No.:	06R0772887-A	**Test Length:**	234

Rod Bearings